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PROPERTIES OF GLASSES AT ELEVATED TEMPERATURES

TECHNICAL DOCUMENTARY REPORT NO. WADC-TR-56-645, Pt VII

August 1962

Directorate of Materials and Processes
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

Project No. 7381, Task No. 738103

(Prepared under Contract No. (D.O.) AF 33(616)59-4 by the National Bureau of Standards, Washington, D.C.; Matthew J. Kerper, author.)

Aeronautical Systems Division, Dir/Materials & Processes, Applications Lab, Wright-Patterson AFB, Ohio.
Rpt Nr WADC-TR-56-645, Pt VII. PROPERTIES OF GLASSES AT ELEVATED TEMPERATURES. Interim report, Aug 62, 80pp, incl illus, tables, & 14 refs.

Unclassified Report

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(over)

of individual glasses over a wide temperature range.

This report contains a study and interpretation of several factors associated with the determination of Young's modulus and the modulus of rupture. The tests were performed on seven commercially available glasses and were conducted from room temperature to several degrees above their strain points.

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FOREWORD

This report was prepared by the National Bureau of Standards under Air Force Order No. AF 33(616)59-4. The contract was initiated under Project No. 7381 "Materials Application" Task No. 738103 - "Data Collection and Correlation." The work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division with Mr. R. E. Wittman as project officer.

This report is an interim report and covers the modulus of rupture and Young's modulus determinations obtained from January 1956 to December 1961.

The mechanical testing was performed in the Glass Section under Mr. C. H. Hahner, the Section Chief. The statistical analysis was made by J. M. Cameron of the Statistical Engineering Section.

ABSTRACT

The ASD program to obtain useful, statistically sound, design criteria on optically transparent window materials of a brittle nature and suitable for military air vehicle applications, is summarized.

Several factors associated with the determination of Young's modulus and the modulus of rupture for seven commercially available glasses are presented and interpreted.

The practical strength of plate glass is dependent on several factors including surface finish, thermal conditioning, cutting techniques and composition. Effects of these variables together with long and short time elevated temperature strength capabilities are shown.

This report has been reviewed and is approved.

W. P. Conrardy

W. P. CONRARDY
Chief, Materials Engineering Branch
Applications Laboratory
Directorate of Materials & Processes

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INTRODUCTION

This project was initiated at the National Bureau of Standards by the Aeronautical Systems Division with the objectives of: 1) developing test methods suitable for measuring the effect of temperature on some of the physical properties of glass, and 2) determining several properties of some presently available commercial glasses that appear to be suitable for aircraft glazing at elevated temperatures. The need for the project is reflected by the discordant strength-temperature results presented in the literature, or as Stanworth (1) says, "The effect of temperature is not at all clearly understood, and it is quite easy to pick out of the literature experimental data showing that the strength increases, decreases, or remains constant with increase in temperature from room temperature upwards."

This report primarily summerizes the results obtained for the modulus of rupture and Young's modulus on the glasses in the program, but also presents other data obtained that is considered pertinent to the testing or utilization of glass. Some of the results obtained or conclusions drawn have previously been reported by other investigators, but because information to support these conclusions have resulted from this project they are reported here, also. Reference is made to some other literature to make this work more useful.

The data obtained in the program have been previously reported in detail in the annual summary reports, "Properties of Glasses at Elevated Temperatures", WADC Technical Report 56-645, Parts I through VI, 1956-1962 (2, 3, 4, 5, 6, 7).

The report is divided into three parts: Part I is the preliminary program consisting chiefly of the testing of plate glass by four different laboratories. Part II is the main program and presents the data obtained on the seven glasses tested at the National Bureau of Standards. Part III presents other data, or analyses of data, obtained in conjunction with the main program.

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APPARATUS, SPECIMENS, AND PROCEDURE

The apparatus used for the modulus of rupture testing fulfilled the requirements specified in ASTM Designation C 158-43 "Flexure Testing of Glass (Flat Glass)", with the exceptions that two point loading over a two inch span was used in place of the single point loading specified, and the entire apparatus was made of Inconel, including the knife edges which ASTM states should be made of brass or mild steel.

All modulus of rupture testing was conducted in an electric furnace that was mounted on the testing machine table. The testing temperature was maintained within ±5 °F. Root-mean-square errors in the modulus of rupture data were estimated to be under three-quarters of one per cent.

During some of the early work the static Young's modulus was determined during the modulus of rupture test by using a commercially available deflectometer that employed a motion transformer. A porcelain rod passed through the bottom of the furnace, contacted the specimen, and transmitted the deflection to the deflectometer. In later work Young's modulus and Poisson's ratio were determined by a dynamic method. The root-mean-square errors for the static Young's modulus determinations were estimated at 1.3 per cent and for the dynamic Young's modulus at less than one-half of one per cent.

The apparatus for determining the modulus of rupture and the static Young's modulus were previously reported (2), and the apparatus for determining the dynamic elastic properties was reported by Spinner (8).

Specimens were made from commercially available glasses and were cut from 1/4 inch thick sheets of glass into 10 inch by 1-1/2 inch specimens, the size recommended by ASTM. No preparation of the edges was given to any specimen, the "as-cut" edges remained on the specimens tested. The surface opposite to the surface with the scored edges was tested in tension. Some specimens had this surface abraded. This abrasion was done by blowing sand against the surface of the specimen. For the testing reported in Part I a 2-1/2 inch by 1 inch rectangular area was abraded on the surface of the specimens. For the testing reported in Part II a uniform weight of graded sand was blown against the specimens from a constant distance with the same amount of air pressure. This produced an abraded

circular area approximately 1-1/4 inches in diameter in the center of the tension surface of the specimens. Specimens referred to as "ground and polished" had no surface abrasion but were tested with the original surface produced by the polishing operation.

For the testing reported in Part I the plate glass was tested in the annealed and tempered conditions. For the testing reported in Part II all seven glasses were tested in the annealed condition and in the semi-tempered and tempered conditions when obtainable.

The semi-tempered and tempered CGW 1723 specimens were warped and a number of the CGW 7900 semi-tempered specimens had small cracks. The semi-tempered CGW 7900 specimens had a considerable formation of alpha cristobalite on the surfaces after heating for 500 hours at 1420°F, while the annealed specimens were not noticeably affected.

Table I lists the seven glasses tested, the manufacturer, the coefficient of expansion, and strain point of each.

Table I. **Glasses Tested**

Glass	Manufacturer	Coefficient of Expansion	Strain Point	
		10^{-7} per °C	°C	°F
Soda Lime Regular Plate	Libbey-Owens-Ford (LOF)	92.0	517	963
PPG 3235 Borosilicate	Pittsburgh Plate Glass Co. (PPG)	62.0	493	920
CGW 7740 Borosilicate	Corning Glass Works (CGW)	32.0	515	959
PPG 6695 Aluminosilicate	Pittsburgh Plate Glass Co.	49.0	660	1220
CGW 1723 Aluminosilicate	Corning Glass Works	42.0	672	1242
CGW 7900 96% Silica	Corning Glass Works	8.0	820	1508
CGW 7940 Fused Silica	Corning Glass Works	5.6	990	1814

ASTM Designation C 158-43 was followed during the modulus of rupture testing; however, the ensuing steps not specified by ASTM were followed:

1) Specimens were stored at 75°F ±5 °F and 50% ±10 % relative humidity.

2) After specimens were measured and readied for testing, they were held under the above conditions for at least 48 hours before testing. This includes specimens tested at elevated temperatures.

3) Specimens tested at 75°F were tested under the above conditions of temperature and humidity.

4) Specimens tested at elevated temperatures were first placed in a laboratory oven and heated to 200°F. They were then placed in the furnace and heated to the testing temperature, held at this temperature for five minutes and then tested. Total time in the furnace for heating, arriving at temperature equilibrium and testing was always under one hour.

5) Some specimens were heated, in annealing furnaces, at the testing temperature for 500 ±2 hours. These specimens were slowly cooled to room temperature and then conditioned and tested in the same manner, and along with, the specimens not heated for 500 hours.

The static Young's modulus was determined on at least three specimens from each test group in Part I during the modulus of rupture determination.

Young's modulus and Poisson's ratio were determined by the dynamic method at 75°F on five specimens from each test group in the testing reported in Part II, before and after heating the specimens for 500 hours. Young's modulus was also determined on three specimens, not previously heat treated, of each glass with increasing temperatures up to the strain point of the glass.

The strain (temper) was measured at 75°F as birefringence at the center of all specimens. The strain was measured before and after the specimens were heated for 500 hours.

The fracture faces of all of the specimens broken in the modulus of rupture testing in the main program were saved and when possible the origin of fracture was located. Fractures were classed as edge when they occurred on one of the edges of the tensile surface and as surface when they occurred on the surface at any place other than the edge. When possible the size of the mirror surface was measured.

The above discussion applies to the testing conducted at the National Bureau of Standards. The testing reported in Part I conducted at the other three laboratories was done in a similar manner.

Part I

PRELIMINARY PROGRAM

The modulus of rupture and Young's modulus were determined on LOF Plate Glass specimens in the annealed and tempered conditions at four different laboratories. These were: Libbey-Owens-Ford Glass Co. (LOF), Pittsburgh Plate Glass Co. (PPG), Wright Air Development Center (WADC)*, and the National Bureau of Standards (NBS). Three of the laboratories conducted tests at 75°F, 400°F, and 550°F; the fourth laboratory conducted tests only at 75°F. The modulus of rupture results obtained by the four laboratories are presented in Table II which gives: the number of specimens tested, the average modulus of rupture, the standard deviation, and the number of edge and surface fractures. Figure 1 is a floating bar chart that pictures for each of the test conditions in Table II, the average modulus of rupture (heavy horizontal line), a standard deviation on either side of the average (hatched areas), and the maximum values obtained (top and bottom horizontal lines).

Comparing the results obtained by the four laboratories for each test condition shows that there is some lack of agreement among the laboratories in the ground and polished test groups, but among the sandblasted test groups the agreement is generally good. To determine whether there was any laboratory bias, a count was made of the number of times in the fourteen test conditions that the modulus of rupture at one laboratory was higher than another. The results are presented in Table III and show that there is no laboratory bias.

The apparatus used to measure the deflection for determining Young's modulus by the static method employed a porcelain rod in contact with the center of the tensile surface of the specimen under test. In order to determine whether this rod affected the strength of the glass, the average modulus of rupture for which the Young's modulus was determined and for the specimens for which it was not determined are compared in Table IV. A one-sided sign test (9) of the values in Table IV indicates that the average modulus of rupture was significantly lower at the 5 per cent level in two laboratories when the Young's modulus was determined by the static method. LOF did not measure Young's modulus at elevated temperatures with a rod in contact with the tensile surface of the specimen, so their results would not be expected to be affected. The above analysis indicates the rod in contact with the tension side of the specimen acted as a stress raiser and weakened the specimen.

*Now Aeronautical Systems Division

Table II. Summary of Results from All Laboratories

Test No.	Laboratories															
	NBS				LOF				WADC				PPG			
	n 1/	f.o. 2/	$\bar{x}$ 3/	S.D. 4/	n	f.o.	$\bar{x}$	S.D.	n	f.o.	$\bar{x}$	S.D.	n	f.o.	$\bar{x}$	S.D.
			psi	psi			psi	psi			psi	psi			psi	psi
1	24	10S,13E	14650	4424	30	18S,12E	15930	2937	28	23S,7E	13540	3062	30	18S,9E	15100	4091
2	10	6S,4E	11090	2962	10	7S,3E	11720	2424	10	6S,3E	11340	3165				
3	10	7S,3E	10260	3472	10	6S,4E	14740	2897	8	5S,2E	13140	2263				
4	24	-	30330	3927	30	16S,9E	33540	4540	30	10S,3E	29020	3497	30	20S,10E	36320	4249
5	10	-	29280	5187	10	-	26750	5195	10	-	30630	2387				
6	10	-	30320	4364	10	-	26400	6265	10	-	28877	3077				
7	10	5S,5E	13610	3461	10	6S,4E	16390	3067	10	5S,4E	10330	2507				
8	30	9S,9E	14410	4702	29	25S,4E	15300	3547	30	17S,10E	10190	1849				
9	10	-	33390	4606	10	-	24270	3789	10	-	27050	2251				
10	30	-	25000	3916	30	9S,4E	24530	4937	30	-	23220	2406				
11	24	19S,5E	10070	606	30	26S,4E	9690	743	29	22S,7E	10130	955	30	19S,11E	10340	1346
12	24	-	23270	1169	30	27S	23650	1031	30	16S	24500	1002	30	29S,1E	25610	1196
13	30	25S,4E	9960	1382	30	26S,4E	10530	871	29	19S,10E	9980	1675				
14	30	-	20750	1549	30	24S	21350	1680	28	-	22010	1295				

1/ Number of specimens tested.

2/ Fracture origin. S indicates fracture originated on the surface of the specimen; E indicates fracture originated on the edge of the specimens.

3/ Average modulus of rupture.

4/ Standard deviation.

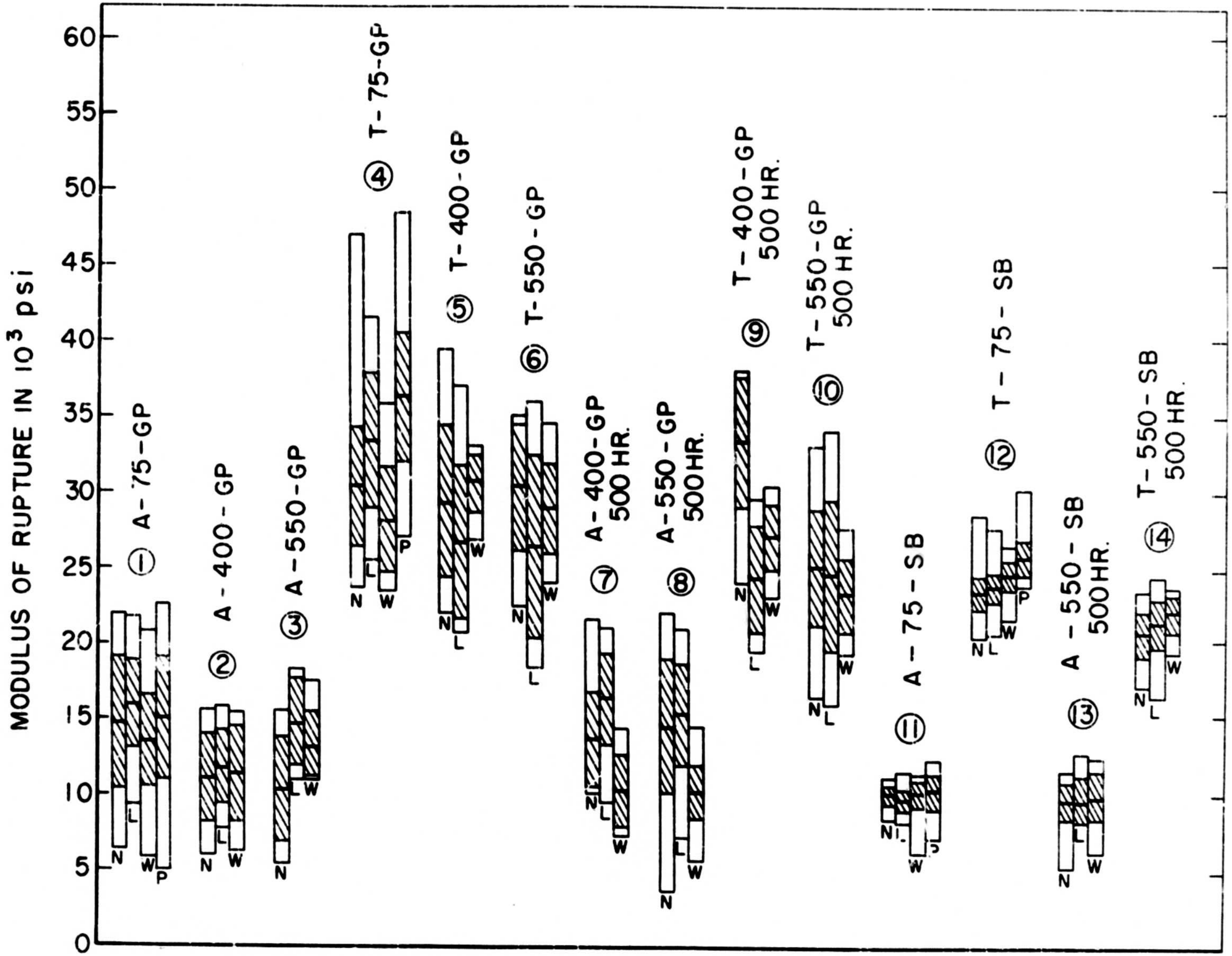


FIGURE I SUMMARY OF MODULUS OF RUPTURE RESULTS FROM ALL LABORATORIES

Table III. Inter-Laboratory Comparisons

Laboratories	Number of Tests in Which the Average Modulus of Rupture is Greater
WADC > NBS	7
NBS > WADC	7
NBS > LOF	5
LOF > NBS	9
LOF > WADC	8
WADC > LOF	6

Table IV. Average Modulus of Rupture Determined With and Without the Porcelain Rod in Contact With the Specimen

Test No.[1/]	NBS		WADC	
	Rod in Contact	Rod Not in Contact	Rod in Contact	Rod Not in Contact
	psi	psi	psi	psi
1	10,760	15,950	13,670	-
2	10,880	11,300	11,060	11,620
3	10,210	10,320	13,500	12,780
4	29,490	30,750	28,760	29,850
5	27,740	30,810	29,140	32,110
6	32,520	29,380	28,740	28,970
7	12,660	14,560	10,290	10,370
8	7,790	15,740	10,500	10,030
9	33,750	33,030	27,020	27,070
10	22,090	25,580	23,170	23,240
11	9,980	10,100	9,770	10,510
12	22,260	23,770	24,330	24,630
13	8,480	9,860	9,870	10,040
14	18,760	21,150	21,350	22,320

1/ Same numbers as used to identify tests in Table II.

The modulus-of-rupture values, obtained without prior involvement with measurements of Young's modulus presented in Table IV were used to study the relationship with temperature. Strength-temperature trends were often shown in two of the laboratories only to have the third laboratory show no trend or the opposite effect. There was rarely complete agreement among all laboratories in showing a definite trend in strength-temperature results. The only statistically significant difference in strength for all 3 laboratories was between tempered specimens tested at 550°F after heating at this temperature for 500 hours and tempered specimens tested at room temperature. The specimens tested at 550°F were weaker. The annealed specimens tested after heating for less than one hour showed a tendency to have a lower strength at 400°F.

Table V presents average modulus of rupture data on annealed glass classified as to fracture origin (surface or edge) determined on specimens not used for static Young's modulus determinations. The results show that for specimens whose fracture originated on the surface, the average modulus of rupture was larger than the average modulus for specimens whose fracture originated on the edge in 18 cases and lower in 4 cases. This difference is significantly different by the sign test at the 5 per cent level.

Table V. Average Modulus of Rupture by Fracture Origin

Test No.[1]	LOF		NBS		WADC		PPG	
	E[2]	S[2]	E	S	E	S	E	S
	psi	psi	psi	psi	psi	psi	psi	psi
1	15290	16300	15490	16020	-	10100	14680	14700
2	8180	13390	13180	10040	7770	12580	-	-
3	12470	14670	9850	10440	11000	11320	-	-
7	20150	14090	16080	13540	9400	9930	-	-
8	16870	15140	13320	14520	8680	10380	-	-
11	9260	9950	9460	10280	10390	10550	9190	11000
13	9080	10800	8700	10060	9030	10560	-	-

1/ Same numbers as used to identify tests in Table II.

2/ S - indicates the fracture originated on the surface of the specimen.
E - indicates the fracture originated on the edge of the specimen.

Table VI gives the Young's modulus as determined by the static method, the number of specimens tested, and the standard deviation for all the test conditions for the three laboratories that determined the modulus of elasticity during the modulus of rupture tests.

The static modulus of elasticity determination on plate glass showed:

1) Sandblasting does not change the modulus of elasticity or reduce the standard deviation of the measurements.

2) The modulus of elasticity of tempered and annealed specimens differed significantly at two laboratories but the results from the third laboratory failed to show a difference. This is an indication of the lack of sensitivity in the static test as employed and because of this lack of sensitivity this test method was not pursued further.

3) One of the laboratories had a significantly higher measurement error than the other two and also had results that were lower than the other two.

Table VI. Summary of Young's Modulus Results from all Laboratories

Test No.[1]	Laboratories								
	LOF			NBS			WADC		
	n[2]	$\bar{x}$[3]	S.D.[4]	n	$\bar{x}$	S.D.	n	$\bar{x}$	S.D.
		10^6psi	10^6psi		10^6psi	10^6psi		10^6psi	10^6psi
1	5	10.83	0.075	6	10.20	0.246	27	10.70	0.336
2	5	10.53	.103	5	10.31	.191	5	10.28	.365
3	5	10.63	.117	5	10.21	.097	4	10.11	.173
4	5	10.19	.225	8	10.44	.284	23	9.80	.364
5	5	10.04	.145	5	10.10	.105	5	9.61	.270
6	5	9.93	.082	2	9.73	.074	3	9.30	.221
7	5	10.27	.165	4	10.34	.127	4	10.25	.104
8	5	10.56	.085	4	10.38	.105	9	9.84	.169
9	5	10.09	.101	4	10.24	.105	4	9.64	.096
10	5	9.14	.155	4	10.13	.084	4	9.66	.397
11	5	10.62	.071	5	10.18	.269	15	10.36	.358
12	5	10.25	.154	7	10.34	.127	13	9.83	.163
13	5	9.15	.085	4	10.33	.147	10	10.46	.303
14	5	9.07	.154	4	10.15	.042	9	9.58	.222

1/ Same numbers as used to identify tests in Table II.

2/ Numbers of specimens tested.

3/ Average Young's modulus.

4/ Standard deviation.

The following conclusions concerning the strength of glass were derived from the Preliminary Program Testing:

1) Difference in strength results can be expected when glass is tested in different laboratories under the same conditions. The laboratories can so show no bias and still produce results different from one another.

2) Sandblasting reduces the average strength and the standard deviation and increases the sensitivity of the modulus of rupture test. By using 10 sandblasted specimens differences of 2000 psi can be detected at the 5 per cent level whereas with 30 ground and polished specimens differences of only 3800 psi can be detected at the 5 per cent level.

3) The deflectometer rod in contact with the tensile surface of the specimen lowered the strength of the specimen.

4) Specimens that had fractures originating on the edge of the specimen were weaker than specimens that had the fracture originating on the surface.

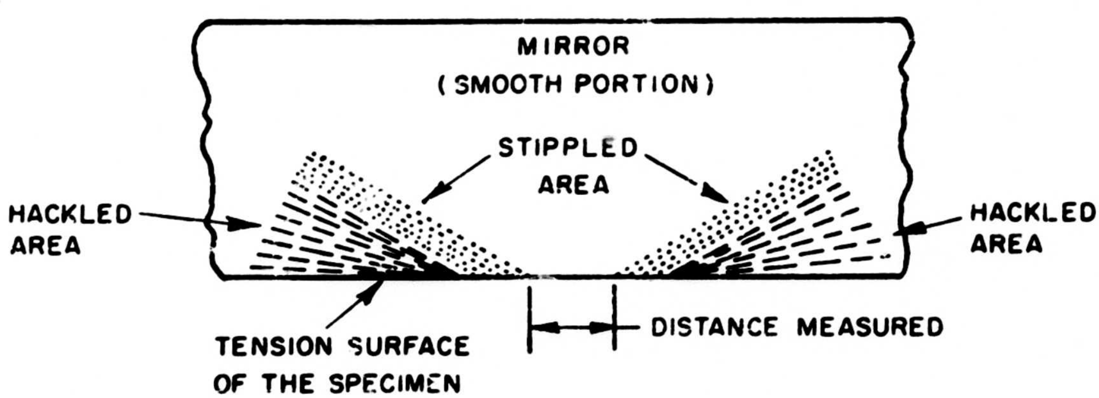
5) Effect of temperature on the strength would be masked if small samples of ground and polished specimens were used.

PART II

MAIN PROGRAM

The modulus of rupture results presented were obtained, except when noted, on sandblasted specimens. The average modulus of rupture values are presented in Figures 2 through 8. The points plotted in the figures are average values for surface fractures only. The average values of the modulus of rupture, radius of the mirror surface, and the respective standard deviations for these values are presented in Tables VII through XXIII.

The mirror radius was determined by measuring the distance between the stippled areas that bound the mirror. This was considered the mirror diameter and dividing by two gave the mirror radius. The measurement was made along the edge of the fracture face that was on the surface of the specimen broken in tension.



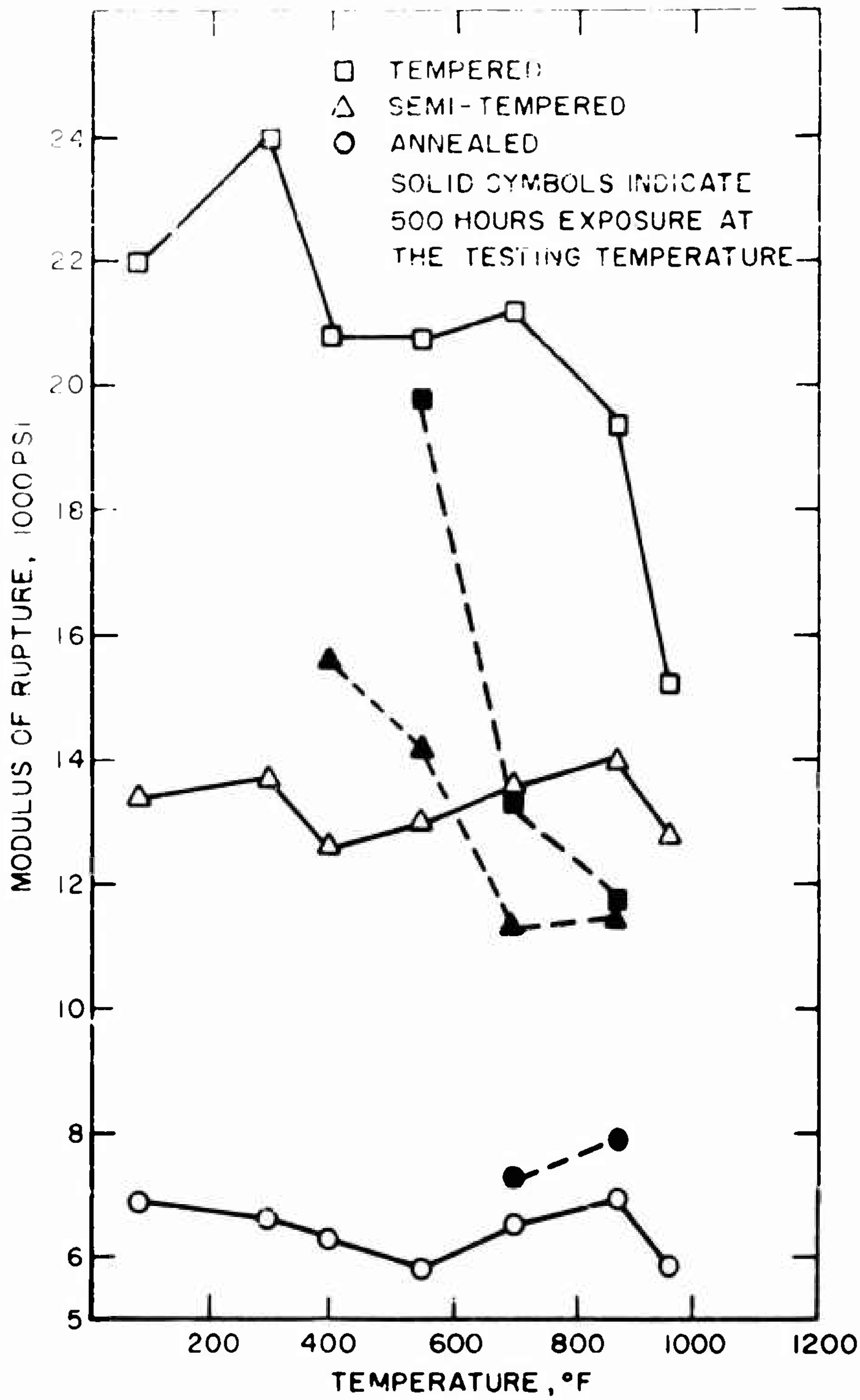


FIGURE 2 MODULUS OF RUPTURE OF SANDBLASTED, LOF PLATE GLASS SPECIMENS AT DIFFERENT TEMPERATURES

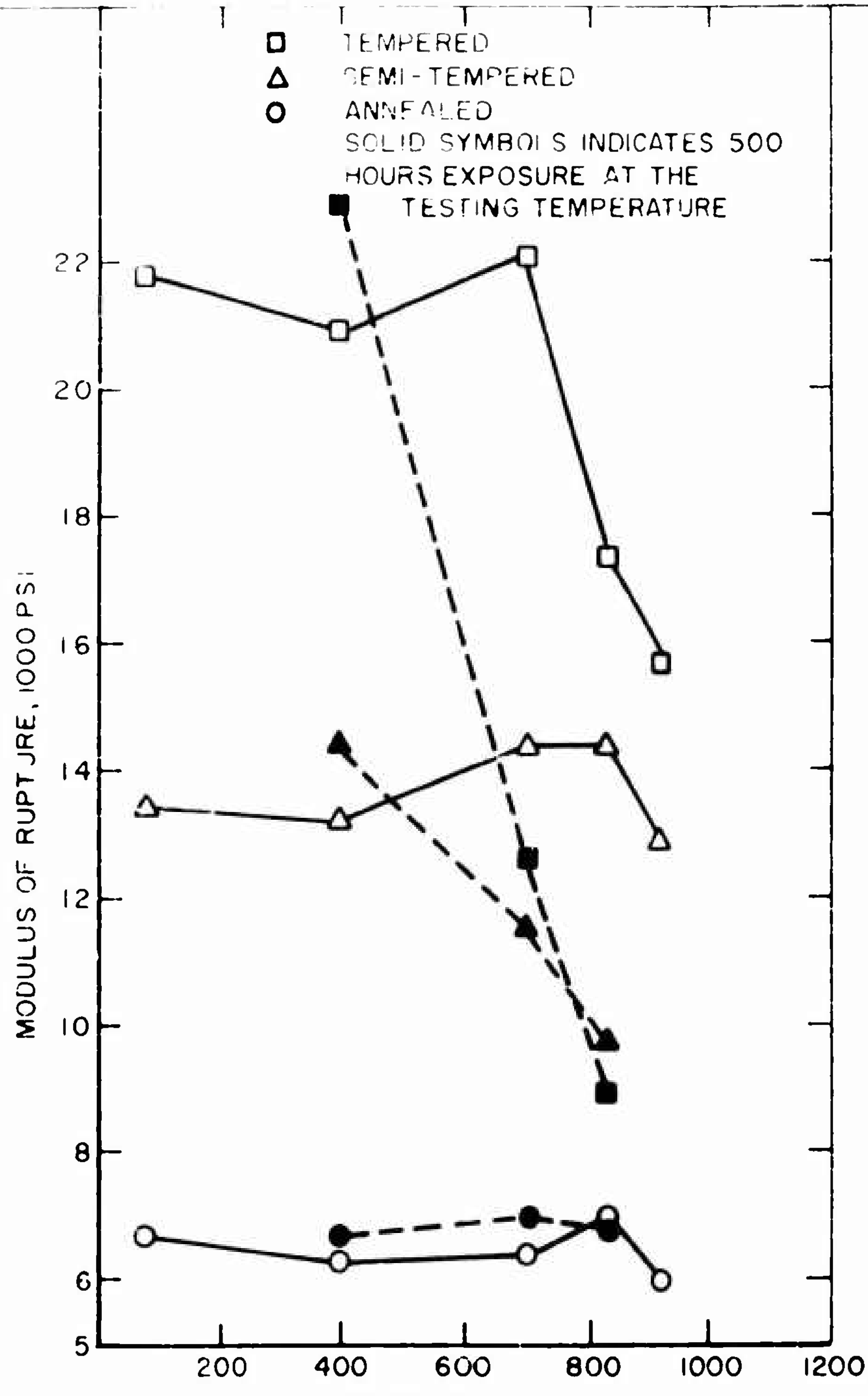


FIGURE 3 MODULUS OF RUPTURE OF SANDBLASTED, PPG 3235 SPECIMENS AT DIFFERENT TEMPERATURES

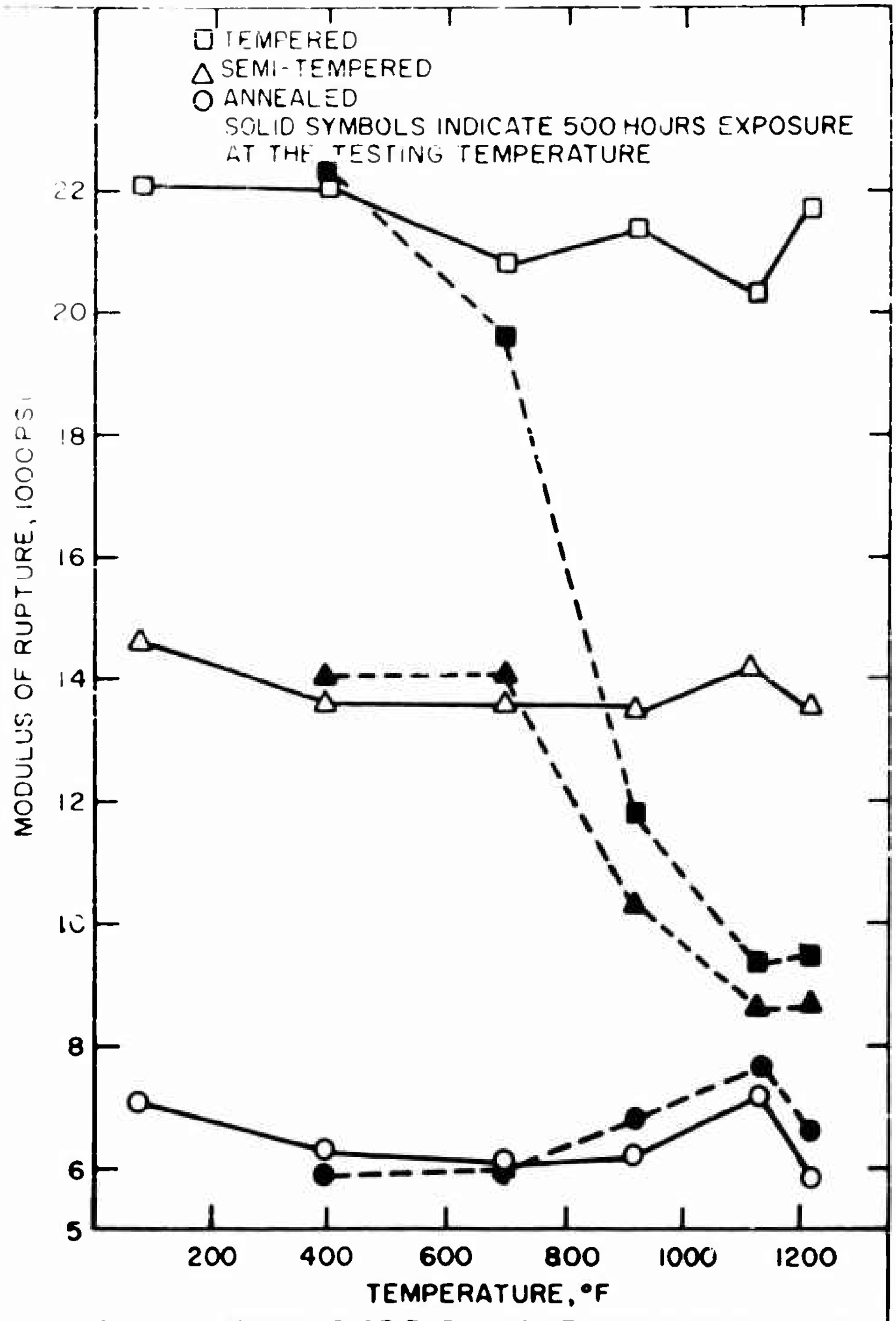


FIGURE 4 MODULUS OF RUPTURE OF SANDBLASTED PPG 6695 SPECIMENS AT DIFFERENT TEMPERATURES

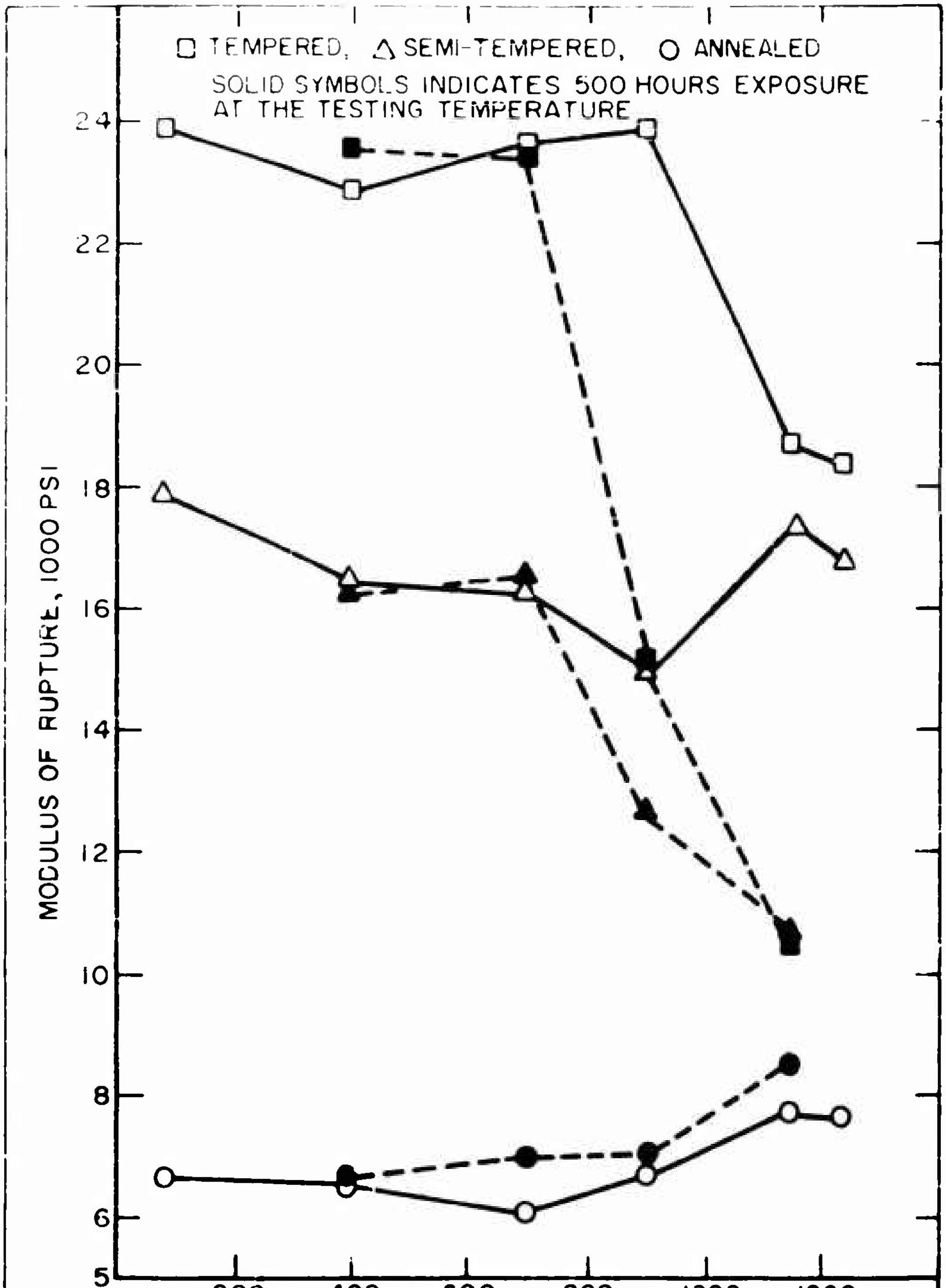


FIGURE 5 MODULUS OF RUPTURE OF SANDBLASTED, CGW 1723 SPECIMENS AT DIFFERENT TEMPERATURES

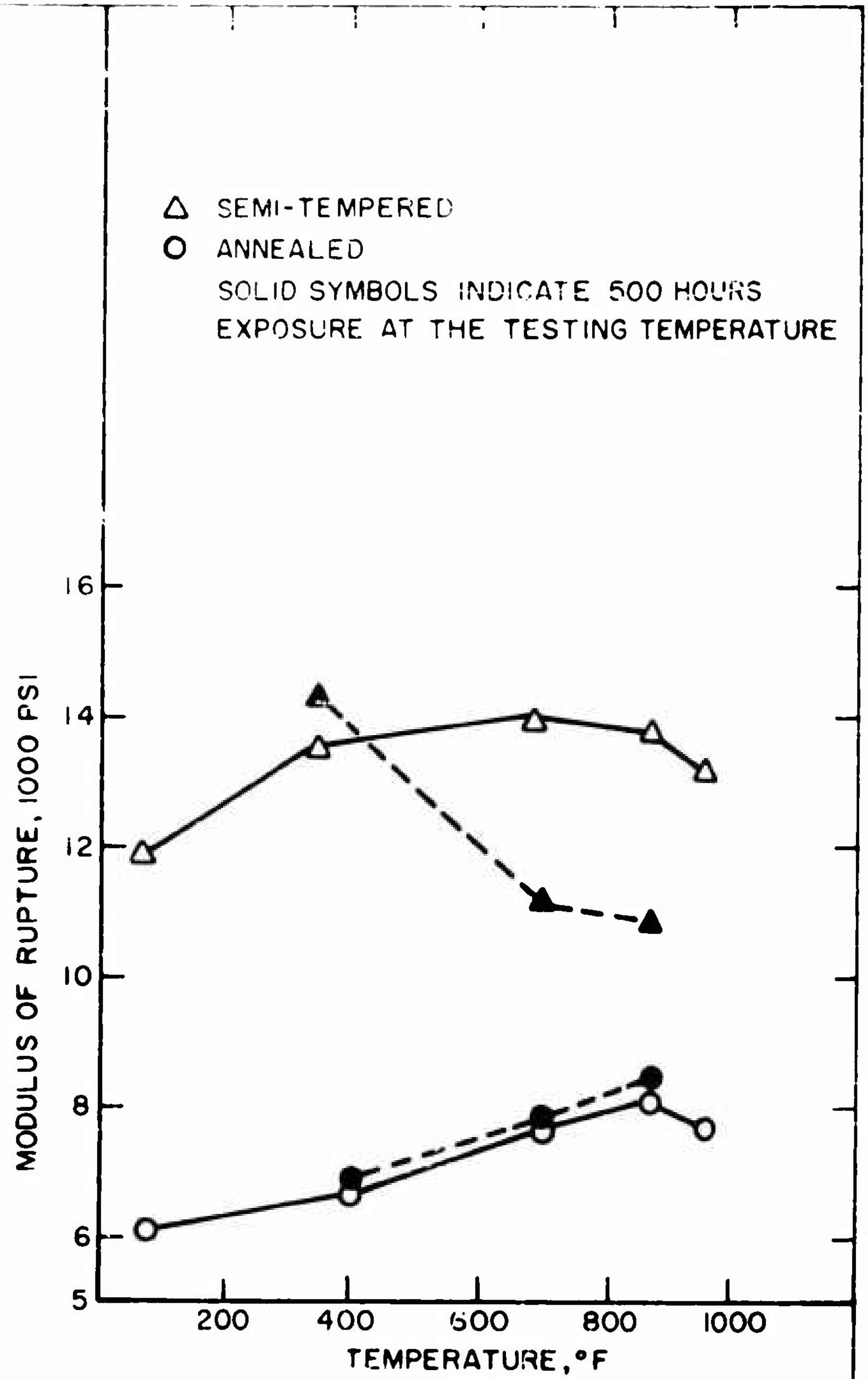


FIGURE 6 MODULUS OF RUPTURE OF SANDBLASTED, CGW 7740 SPECIMENS AT DIFFERENT TEMPERATURES

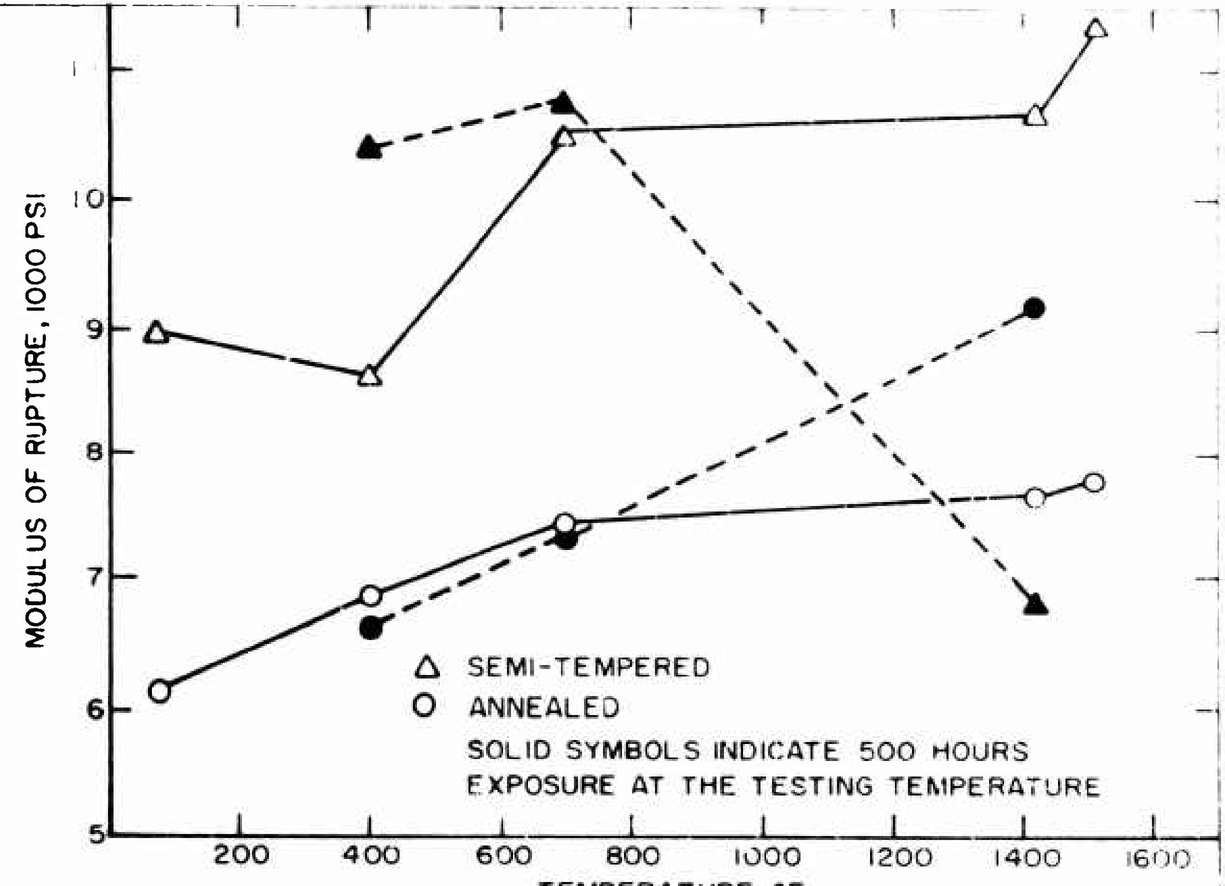


FIGURE 7 MODULUS OF RUPTURE OF SANDBLASTED, CGW 7900 SPECIMENS AT DIFFERENT TEMPERATURES

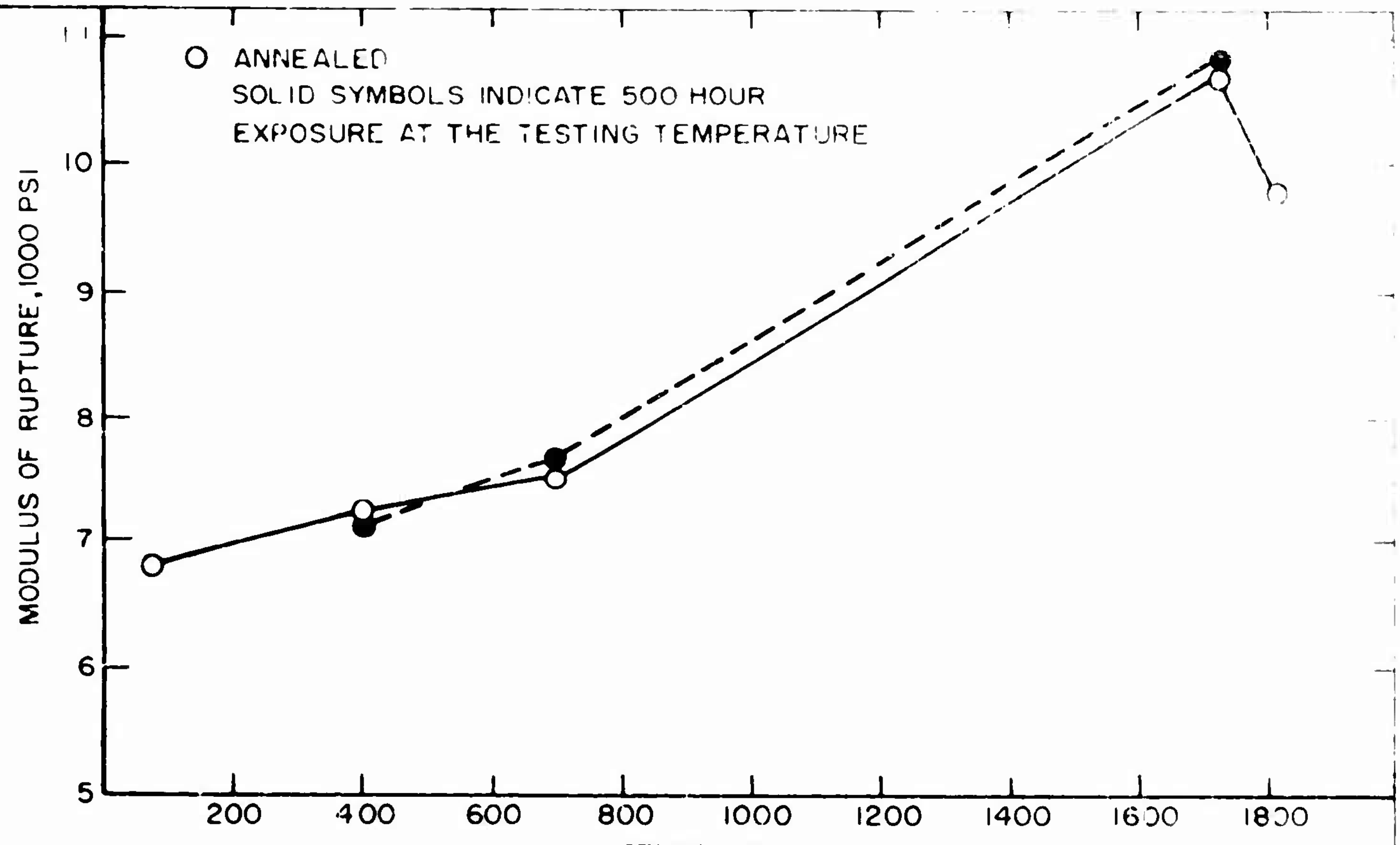


FIGURE 8 MODULUS OF RUPTURE OF SANDBLASTED, CGW 7940 SPECIMENS AT DIFFERENT TEMPERATURES

Table VII. Modulus of Rupture for Annealed, Sandblasted, LOF Plate Glass Specimens

Testing Temperature °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches
75	1	S	9	6900	579	9	0.064	0.012
		E	6	5030	779	6	0.198	0.043
75[7]	1	S	12	11320	2400	12	0.028	0.012
		E	18	11310	2724	18	0.030	0.019
300	1	S	10	6620	634	10	0.071	0.030
		E	5	6120	507	5	0.152	0.064
400	1	S	13	6330	790	13	0.079	0.037
		E	2	5300	283	2	0.174	0.074
550	1	S	15	5870	480	14	0.081	0.033
		E	0	--	-	0	--	--
700	1	S	13	6550	544	13	0.064	0.018
		E	2	5200	424	2	0.220	0.006
700	500	S	15	7260	580	15	0.052	0.022
		E	0	--	-	0	--	--
870	1	S	12	6990	417	10	0.057	0.011
		E	3	6470	874	3	0.136	0.038
870	500	S	14	7980	614	14	0.038	0.009
		E	1	6900	-	1	0.079	--
963	1	S	11	5900	1236	10	.057	.012
		E	4	5325	-	-	--	--

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge of the specimen.

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ These specimens were not sandblasted but had the original ground and polished surface.

Table VIII. Modulus of Rupture for Semi-Tempered, Sandblasted, LOF Plate Glass Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center, Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S	15	13410	747	15	0.046	0.005	15	1776	71			
		E	0	-	-	0	-	-	0	-	-			
75[7]	1	S	26	21070	2688	18	0.018	0.007	26	1808	59			
		E	1	25000	-	1	-	-	1	1890	-			
300	1	S	15	13680	1225	15	0.047	0.004	15	1817	41			
		E	0	-	-	0	-	-	0	-	-			
400	1	S	15	12650	519	15	0.049	0.005	15	1786	76			
		E	0	-	-	0	-	-	0	-	-			
400	500	S	15	15610	928	14	0.031	0.007	15	1801	71	15	1785	67
		E	0	-	-	0	-	-	0	-	-	0	-	-
550	1	S	15	13040	910	14	0.048	0.004	15	1809	78			
		E	0	-	-	0	-	-	0	-	-			
550	500	S	15	14180	641	15	0.035	0.004	15	1756	78	15	1597	59
		E	0	-	-	0	-	-	0	-	-	0	-	-
700	1	S	15	13570	414	15	0.041	0.005	15	1775	73			
		E	0	-	-	0	-	-	0	-	-			
700	500	S	11	11290	1542	11	0.036	0.017	11	1813	83	11	830	59
		E	4	10150	2200	4	0.091	0.057	4	1761	107	4	799	101
870	1	S	14	13990	795	11	0.030	0.004	14	1776	74			
		E	1	11100	-	1	-	-	1	1365	-			
870	500	S	8	11510	1795	5	0.021	0.005	8	1767	95	8	55	-
		E	7	8560	1816	7	0.061	0.031	7	1832	72	7	55	-
963	1	S	12	12800	1488	10	0.033	0.005	10	1786	56	-	-	-
		E	3	10770										

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ These specimens were not sandblasted but had the original ground and polished surface. Thirty specimens were tested but the location of the fracture origin could not be determined on three specimens.

Table IX. Modulus of Rupture for Tempered, Sandblasted, LOF Plate Glass Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Break[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S	15	21990	681	14	0.034	0.003	15	3534	170			
		E	0	-	-	0	-	-	0	-	-			
75[7]	1	S	26	29600	2826	17	0.021	0.007	26	3548	128			
		F	1	34800	-	1	0.033	-	1	3605	-			
300	1	S	15	24010	2920	15	0.034	0.003	15	3554	125			
		E	0	-	-	0	-	-	0	-	-			
400	1	S	15	20820	1519	13	0.039	0.004	15	3515	115			
		E	0	-	-	0	-	-	0	-	-			
550	1	S	15	20840	771	14	0.036	0.002	15	3460	79			
		E	0	-	-	0	-	-	0	-	-			
550	500	S	15	19820	619	14	0.033	0.002	15	3491	109	15	2889	80
		E	0	-	-	0	-	-	0	-	-	0	-	-
700	1	S	15	21180	1685	14	0.038	0.004	15	3536	116			
		E	0	-	-	0	-	-	0	-	-			
700	500	S	13	13310	857	10	0.035	0.010	13	3526	110	13	1339	21
		E	2	12050	212	2	0.061	0.014	2	3398	95	2	1330	28
870	1	S	15	19370	1135	15	0.026	0.004	15	3427	90			
		E	0	-	-	0	-	-	0	-	-			
870	500	S	10	11580	1186	10	0.017	0.004	10	3518	106	10	80	-
		E	5	10580	1119	5	0.033	0.016	5	3512	112	5	80	-
963	1	S	15	15200	3230	12	0.027	0.007	14	3607	131	-	-	-
		E	0	-	-	-	-	-	-	-	-	-	-	-

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ These specimens were not sandblasted but had the original ground and polished surface. Thirty specimens were tested but the location of the fracture origin could not be determined on three specimens.

Table X. Modulus of Rupture for Annealed, Sandblasted PPG 3235 Specimens

Testing Temperature °F	Exposure[1] Hours	Location of Break[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches
75	1	S	15	6680	347	15	0.088	0.011
		E	0	-	-	0	-	-
75[7]	1	S	9	11140	2991	9	0.028	0.015
		E	21	9310	2199	20	0.077	0.056
400	1	S	14	6270	611	14	0.098	0.020
		E	1	6700	-	1	0.098	-
400	500	S	15	6670	880	15	0.085	0.021
		E	0	-	-	0	-	-
700	1	S	15	6380	739	15	0.100	0.032
		E	0	-	-	0	-	-
700	500	S	13	6990	476	13	0.069	0.012
		E	2	6350	919	2	0.188	0.050
830	1	S	15	7000	504	15	0.073	0.014
		E	0	-	-	0	-	-
830	500	S	15	6770	546	15	0.073	0.015
		E	0	-	-	0	-	-
920	1	S	15	6000	830	14	0.089	0.006
		E	0					

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly at room temperature, and then tested in the same manner as the one hr specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ These specimens were not sandblasted but had the original ground and polished surface.

Table XI. Modulus of Rupture for Semi-Tempered, Sandblasted, PPG 3235 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S	15	13380	682	15	0.058	0.005	15	2564	135			
		E	0	-	-	0	-	-	0	-	-			
75[7]	1	S	30	19830	2951	26	C.027	0.011	30	2577	68			
		E	0	-	-	0	-	-	0	-	-			
400	1	S	15	13220	1299	15	0.060	0.007	15	2541	105			
		E	0	-	-	0	-	-	0	-	-			
400	500	S	15	14430	682	15	0.054	0.006	15	2554	88	15	2503	80
		E	0	-	-	0	-	-	0	-	-	0	-	-
700	1	S	15	14400	651	15	0.047	0.004	15	2576	88			
		E	0	-	-	0	-	-	0	-	-			
700	500	S	13	11520	402	13	0.043	0.006	13	2550	73	13	1227	36
		E	2	10300	1839	2	0.092	0.081	2	2628	86	2	1205	7
830	1	S	15	14420	884	15	0.043	0.008	15	2527	53			
		E	0	-	-	0	-	-	0	-	-			
830	500	S	14	9710	1076	14	0.037	C.010	14	2585	66	14	40	-
			1	7300	-	1	0.098	-	1	2495	-	1	40	-
920	1	S	15	1290C	1698	15	0.049	0.002	15	2404	52	-	-	-
		E	0											

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ These specimens were not sandblasted but had the original ground and polished surface.

Table XII. Modulus of Rupture for Tempered, Sandblasted, PPG 3235 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Break[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center, Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S	15	21770	823	15	0.047	0.005	15	4916	162			
		E	0	-	-	0	-	-	0	-	-			
75[7]	1	S	21	28910	2845	15	0.025	0.004	21	4865	129			
		E	9	28120	3755	2	0.057	0.011	9	4897	162			
400	1	S	15	21900	929	15	0.047	0.003	15	4861	161			
		E	0	-	-	0	-	-	0	-	-			
400	500	S	15	22860	1591	15	0.042	0.006	15	4797	90	15	4666	76
		E	0	-	-	0	-	-	0	-	-	0	-	-
700	1	S	15	22110	609	15	0.039	0.006	15	4787	195			
		E	0	-	-	0	-	-	0	-	-			
700	500	S	10	12590	866	10	0.039	0.005	10	4827	261	10	2568	768
		E	5	11560	688	5	0.057	0.038	5	4883	102	5	2647	72
830	1	S	15	17350	3438	15	0.036	0.008	15	4948	122			
		E	0	-	-	0	-	-	0	-	-			
830	500	S	10	8900	1736	10	0.043	0.017	10	4942	113	10	160	-
		E	5	7280	1998	5	0.156	0.120	5	4847	89	5	160	-
920	1	S	15	15700	3321	14	0.036	0.002	15	4867	141	-	-	-

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ These specimens were not sandblasted but had the original ground and polished surface.

Table XIII. Modulus of Rupture for Annealed, Sandblasted, PPG 6695 Specimens.

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	$\bar{x}$[4] psi	S.D.[5] psi	Mirror Size[6] n	$\bar{x}$ Inches	S.D. Inches
75[7]	1	S	21	12184	4362	20	0.055	0.049
		E	9	10751				
75	1	S	12	7059	2085	10	.126	.024
		E	3	6633				
400	1	S	15	6240	674	15	.157	.048
		E	0					
400	500	S	11	5887	737	11	.157	.039
		E	4	5312				
700	1	S	14	6082	696	14	.144	.033
		E	1	5748				
700	500	S	13	5956	582	12	.144	.031
		E	2	5077				
915	1	S	15	6256	593	15	.121	.044
		E	0					
915	500	S	15	6850	367	15	.081	.024
		E	0					
1130	1	S	12	7027	645	12	.069	.037
		E	0					
1130	500	S	11	7614	614	11	.084	.037
		E	1	7470				
1220	1	S	15	5796	852	15	.115	.041
		E	0					
1220	500	S	15	6532	747	15	.072	.023
		E	0					
1256[8]	1	S	12	7900	888	15	.069	.027
		E	0					

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " "

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Specimen surface ground and polished, not sandblasted.

8/ Tested in a shorter time than other specimens.

Table XIV. Modulus of Rupture for Semi-Tempered, Sandblasted, PPG 6695 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\overline{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\overline{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\overline{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\overline{x}$ mu/in	After Heating S.D. mu/in
75[7]	1	S E	29 1	22246 19136	3183	26	0.029	0.010	29	2125	93			
75	1	S E	15 0	11660	993	15	.067	.005	15	2029	81			
400	1	S E	15 0	13648	550	14	.078	.010	15	1909	59			
400	500	S E	15 0	14048	1514	15	.072	.012	15	1896	54	15	1896	54
700	1	S E	15 0	13605	568	15	.071	.009	15	1993	79			
700	500	S E	15 0	14147	500	15	.066	.009	15	1950	79	15	1821	73
915	1	S E	15 0	13460	701	15	.070	.005	15	1987	62			
915	500	S E	15 0	10319	684	15	.052	.007	15	1958	51	15	687	15
1130	1	S E	15 0	14197	1133	15	.060	.006	15	2019	82			
1130	500	S E	12 3	8563 8391	915	12	.065	.047	12	1938	53	12	negligible	
1220	1	S E	15 0	13614	736	15	.060	.006	15	1925	60			
1220	500	S E	12 3	8739 7016	1679	12	.065	.047	12	1913	58	12	"	
1256[8]	1	S E	12 0	13090	743	12	.033	.005	12	1968				

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E indicates fracture originated on the edge of the specimen.

3/ n indicates number of specimens tested.

4/ $\overline{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Specimen surface ground and polished, not sandblasted.

8/ Tested in a shorter time than other specimens.

Table XV. Modulus of Rupture for Tempered, Sandblasted, PPG 3695 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75[7]	1	S E	28 2	26689 24658	3554	22	0.032	0.009	28	3509	91			
75	1	S E	15 0	22105	1654	-	-	-	15	3499	173			
400	1	S E	15 0	22008	1325	15	.056	.005	15	3480	151			
400	500	S E	15 0	22347	1343	14	.053	.007	15	3499	133	15	3499	133
700	1	S E	15 0	20828	2317	14	.055	.004	15	3561	100			
700	500	S E	15 0	19600	876	13	.058	.005	15	3541	128	15	3093	98
915	1	S E	15 0	21360	814	13	.048	.005	15	3526	133			
915	500	S E	13 2	11798 11317	820	12	.045	.007	13	3547	124	13	986	34
1130	1	S E	15 0	20313	1751	11	.051	.007	15	3543	89			
1130	500	S E	13 2	9355 8309	884	11	.043	.014	13	3264	371	13	negligible	
1220	1	S E	15	21750	1261	14	.043	.004	15	3548	76			
1220	500	S E	11 3	9492 6903	1530	11	.044	.024	11	3508	93	11	"	
1256[8]	1	S E	11 0	14349	1455	10	.027	.007	11	3469				

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.
2/ S indicates fracture originated on the surface of the specimen.
E indicates fracture originated on the edge of the specimen.
3/ n indicates number of specimens tested.
4/ $\bar{x}$ indicates average.
5/ S.D. indicates standard deviation.
6/ Radius of the smooth portion of the fracture face.
7/ Specimen surface ground and polished, not sandblasted.
8/ Tested in a shorter time than other specimens.

Table XVI. Modulus of Rupture for Annealed, Sandblasted, CGW 1723 Specimens

Testing Temperature °F	Exposure[1] Hours	Location of Break[2]	Modulus of Rupture n[3]	$\bar{x}$[4] psi	S.D.[5] psi	Mirror Size[6] n	$\bar{x}$ Inches	S.D. Inches
75	1	S	12	6630	788	12	0.115	0.049
		E	2	6200				
400	1	S	13	6560	728	13	.116	.053
		E	1	6700				
400	500	S	13	6650	706	13	.119	.052
		E	2	6300				
700	1	S	14	6070	637	14	.139	.062
		E	0					
700	500	S	14	6990	908	14	.094	.053
		E	1	7000				
1150	1	S	13	7790	787	13	.072	.023
		E	2	6900				
1150	500	S	12	8520	1151	12	.060	.028
		E	3	5930				
1242	1	S	15	7700	890	15	.090	.048
		E	0					
1296[7]	1	S	12	7630	479	12	.069	.009
		E	0					

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Tested in a shorter time than the other specimens.

Table XVII. Modulus of Rupture for Semi-Tempered, Sandblasted, CGW 1723 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S E	15 0	17980	1119	15	0.047	0.006	15	2336	123			
400	1	S E	15 0	16530	1225	15	.049	.006	15	2093	233			
400	500	S E	15 0	16310	1408	15	.049	.005	15	2081	260	15	207[illegible]	258
700	1	S E	15 0	16350	1267	15	.045	.005	15	2164	240			
700	500	S E	15 0	16650	1708	15	.044	.008	15	2040	294	15	1949	28[illegible]
1150	1	S E	12 3	17520 16330	1500	12	.026	.003	12	2256	297			
1150	500	S	12 3	10850 9200	1100	10	.037	.017	12	2028	236	12	20	-
1242	1	S E	15 0	16800	1655	14	.030	.004	-	-	-	-	-	-
1296[7]	1	S E	12	1[illegible]720	454	12	.032	.004						

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " edge of the specimen.

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Tested in a shorter time than the other specimens.

Table XVIII. Modulus of Rupture for Tempered, Sandblasted, CGW 1723 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S E	15 0	23950	1144	15	0.040	0.004	15	3574	242			
400	1	S E	15 0	22930	1125	15	.043	.004	15	3578	176			
400	500	S E	15 0	23630	1738	15	.040	.004	15	3674	145	15	3636	185
700	1	S E	15 0	23780	1302	15	.039	.003	15	3676	138			
700	500	S E	15 0	23370	988	15	.038	.003	15	3593	149	15	3352	152
1150	1	S E	12 3	18690 13800	3017	12	.024	.006	15	3670	130			
1150	500	S E	4 9	10450 8700	2398 -	4	.039	.016	4	3895	126	4	20	-
1242	1	S E	15 0	18400	1987	13	.028	.007	-	-	-	-	-	-

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

Table XIX. Modulus of Rupture for Annealed, Sandblasted, CGW 7740 Specimens.

Testing Temperature °F	Exposure[1] Hours	Location of Break[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches
75	1	S	13	6100	233	13	0.097	0.0114
		E	2	4300	-	-	-	-
400	1	S	12	6700	557	12	.076	.0182
		E	3	5800	-	-	-	-
400	500	S	13	6900	1216	12	.059	.0085
		E	2	4600	-	-	-	-
700	1	S	14	7700	705	14	.060	.0164
		E	1	6900	-	-	-	-
700	500	S	14	7750	718	14	.054	.0152
		E	1	7700	-	-	-	-
870	1	S	11	8100	467	11	.050	.0090
		E	4	8200	-	-	-	-
870	500	S	13	8500	595	13	.042	.0117
		E	2	5500	-	-	-	-
960	1	S	13	7700	546	12	.0565	.0093
		E	2	8200	-	-	-	-
995[7]	1	S	15	8220	470	15	.038	.0043
		E	0					

1/ One hour indicates specimens were tested after less than one hr. exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " "

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Tested in a shorter time than the other specimens.

Table XX. Modulus of Rupture for Semi-Tempered, Sandblasted, CGW 7740 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S	15	11900	547	15	0.064	0.0041	15	1729	73			
		E	0											
400	1	S	15	13600	1894	14	.049	.0048	15	1713	66			
		E	0											
400	500	S	15	14300	565	15	.042	.0036	15	1750	77	15	1797	76
		E	0											
700	1	S	15	14100	1253	14	.044	.0068	15	1688	138			
		E	0											
700	500	S	12	11200	731	12	.044	.0081	12	1757	34	12	749	37
		E	3	10400		-	-	-	3	1760	-	3	763	-
870	1	S	15	13800	1929	15	.041	.0106	15	1750	86			
		E	0											
870	500	S	5	10900	611	4	.032	.0062	5	1754	90	5	negli-gible	-
		E	10	7900	-	-	-	-	10	1752	-	10	"	-
960	1	S	14	13200	1673	14	.038	.0047	14	1731	86			
		E	1	14600	-	-	-	-	1	1605	-			
995[7]	1	S	15	12940	900	13	.031	.0039						
		E	0											

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E indicates fracture originated on the edge of the specimen.

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Tested in a shorter time than the other specimens.

Table XXI. Modulus of Rupture for Annealed, Sandblasted, CGW 7900 Specimens

Testing Temperature °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	$\bar{x}$[4] psi	S.D.[5] psi	Mirror Size[6] n	$\bar{x}$ Inches	S.D. Inches
75	1	S	13	6150	627	12	0.087	0.029
		E	2	4700	-			
400	1	S	10	6870	514	10	.063	.019
		E	3	7350	-			
400	500	S	8	6640	571	8	.073	.016
		E	6	5330	-			
700	1	S	9	7460	477	8	.050	.009
		E	6	7050				
700	500	S	14	7360	511	14	.058	.014
		E	1	6200	-			
1420	1	S	11	7670	826	11	.046	.008
		E	4	7300	-			
1420	500	S	10	9020	644	8	.032	.006
		E	5	8900	-			
1508	1	S	12	7800	494	12	.055	.0076
		E	3	6600	-			
1787[7]	1	S	15	7140	565	13	.046	.007
		E	0					

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Tested in a shorter time than the other specimens.

Table XXII. Modulus of Rupture for Semi-Tempered, Sandblasted, CGW 7900 Specimens

Testing Temp. °F	Exposure[1] Hours	Location of Breaks[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches	Birefringence of Center Before Heating n	Before Heating $\bar{x}$ mu/in	Before Heating S.D. mu/in	After Heating n	After Heating $\bar{x}$ mu/in	After Heating S.D. mu/in
75	1	S	14	8990	2034	13	0.065	0.021	14	900	314			
		E	0											
400	1	S	10	8620	1596	8	.053	.008	10	739	326			
		E	3	8170	-									
400	500	S	14	10390	1157	13	.045	.007	14	918	189	14	913	134
		E	1	12200	-									
700	1	S	12	10460	1120	12	.048	.0033	12	917	245			
		E	0											
700	500	S	13	10750	1825	12	.042	.008	13	915	162	13	907	160
		E	1	10500										
1420	1	S	14	10730	1334	14	.038	.0029	14	876	236			
		E	1	11900										
1420	500	S	9	6800	1704	8	.097	.050	9	987	205	9	40	-
		E	6	7400	-									
1508	1	S	13	11700	1533	12	.033	.0050	13	795	284			
		E	2	5300	-									
1787[7]	1	S	15	10000	565	9	.030	.007						
		E	0											

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimens.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Tested in a shorter time than the other specimens.

Table XXIII. Modulus of Rupture for Annealed, Sandblasted, CGW 7940 Specimens

Testing Temperature °F	Exposure[1] Hours	Location of Break[2]	Modulus of Rupture n[3]	Modulus of Rupture $\bar{x}$[4] psi	Modulus of Rupture S.D.[5] psi	Mirror Size[6] n	Mirror Size $\bar{x}$ Inches	Mirror Size S.D. Inches
75	1	S E	14 1	6800 6100	306	13	0.070	0.011
400	1	S E	13 0	7240	553	13	.057	.013
400	500	S E	14 0	7170	750	14	.049	.014
700	1	S E	15 0	7500	578	15	.056	.024
700	500	S E	12 3	7680 7000	389	12	.051	.008
1724	1	S E	15 0	10690	2206	15	.033	.007
1724	500	S E	12 3	10830 9500	1180	10	.027	.008
1814	1	S E	15 0	9800	848	12	.038	.0051
1922[7]	1	S E	12 0	12490	2270			

1/ One hour indicates specimens were tested after less than one hour exposure at the indicated testing temperature. Five hundred hours indicates that specimens were heated at the test temperature for 500 hours, cooled slowly to room temperature, and then tested in the same manner as the one hour specimens.

2/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

3/ n indicates number of specimens tested.

4/ $\bar{x}$ indicates average.

5/ S.D. indicates standard deviation.

6/ Radius of the smooth portion of the fracture face.

7/ Tested in a shorter time than the other specimens.

The results for the annealed glass show that when tested with less than one hour exposure at the testing temperature, LOF Plate Glass, PPG 3235, PPG 6695, and CGW 1723 all showed a decrease in strength from the room temperature value with increasing temperature. This was followed by an increase in strength as the strain point temperature was approached until a value of the strength that was as great or greater than the room temperature value was reached. These decreases in strength compared to the strength at 73°F varied from about six percent to about 15 percent and were statistically significant at the 5% level for LOF Plate Glass and PPG 6695. The strength of CGW 7740, CGW 7900, and CGW 7940 increased with increasing temperature up to the strain point. At the strain point all of the glasses with the exception of CGW 7900 showed a decrease in strength. CGW 7900 showed a slight increase in strength at the strain point.

Heating for 500 hours did not adversely affect the strength of annealed glass, but it tended to strengthen the glass, expecially at the higher temperatures. When only the highest two treatment temperatures for each glass are considered they show that in 12 cases out of 14 the heat treatment increased the strength of the glass. This is significant by the sign test at the 5% level.

The figures show for semi-tempered and tempered glasses tested at temperatures at least 400°F below the strain point of the glass the 500 hour exposure to elevated temperatures did not reduce the strength of these glasses, but as the strain point of the glass is approached the strength decreases greatly. When tested with less than one hour exposure to the testing temperature, all of the semi-tempered specimens retained their strength up to 120°F below the strain point. The fully tempered glasses showed a loss in strength at these temperatures. The four glasses available in both tempered and semi-tempered form show that after exposure for 500 hours at temperatures 120°F below their respective strain points the strengths of both the tempered and semi-tempered specimens are close to one another. Also, after this exposure, these glasses have no appreciable strain remaining; however, in every case except for CGW 7900 the strength values of the semi-tempered and tempered specimens are higher than those of the annealed specimens heated and tested under the same conditions. The CGW 7900 specimens had crystallized surfaces and this undoubtedly accounts for part of the loss of strength.

Considering all seven glasses, heating did not appear to affect the number of fractures originating on the surface for annealed glass; but heating at higher temperatures, especially for 500 hours, did reduce the number of fractures originating on the surface in the semi-tempered and tempered specimens.

Considering all seven glasses, and all conditions of temperature, Table XXIV shows the number of test groups that had edge breaks, the number of groups in which the surface breaks were stronger and the number of groups in which the edge breaks were stronger.

Table XXIV. Test Groups that had Edge Fractures

Condition of Temper[1]	No. of Groups in Which Edge Breaks Occurred	No. of Groups in Which Surface Breaks Were Stronger	No. of Groups in Which Edge Breaks Were Stronger
A	42	37	5
S	21	14	7
T	12	11	1

1/ A - Annealed, S - Semi-tempered, T - Tempered.

The data shows that the glass is stronger when the fractures occur on the surface than when the fractures occur on the edge of the specimens. This is significant by a sign test at the one percent level for the annealed and tempered specimens and at the 25% level for the semi-tempered specimens.

MODULUS OF RUPTURE DETERMINED AT THE MAXIMUM TESTING TEMPERATURE

The maximum testing temperature is used here as the temperature at which the testing machine crosshead speed had to be slightly increased in order to maintain the required loading rate of 10,000 psi per minute. Below the maximum test temperature the glasses tested obeyed Hooke's law during the modulus of rupture testing. Above the maximum test temperature the glass would yield with load and required an increase in crosshead speed to maintain the required loading rate.

The maximum testing temperature was found by testing at increasingly higher temperatures until the testing machine crosshead speed had to be slightly increased in order to maintain the required rate of loading. After specimens had been heated to the strain point it took about two minutes to reach the maximum test temperature. Specimens were held at temperature for two minutes before testing.

The maximum test temperature and the moduli of rupture obtained at these temperatures are presented with the other modulus of rupture data for the respective glasses. However, the data are summerized in Table XXV which gives the glasses tested, their strain point and maximum test temperature, and the modulus of rupture at that temperature.

Table XXV. Modulus of Rupture at Maximum Testing Temperature

Glass	Degree of Temper[1]	Strain Point	Maximum Test Temper-ature	Location of Break[2]		Modulus of Rupture at Maximum Test Temperature			Mirror Size[6]		
						n[3]	$\overline{x}$[4]	S.D.[5]	n	$\overline{x}$	S.D.
		°F	°F				psi	psi		Inches	Inches
PPG 6695	A	1220	1256	S		12	7900	888	12	0.069	0.0270
PPG 6695	ST	1220	1256	S		12	13090	743	12	.033	.0052
PPG 6695	T	1220	1256	S		11	14410	1521	10	.027	.0061
CGW 1723	A	1242	1296	S		12	7630	479	12	.069	.0092
CGW 1723	ST	1242	1296	S		12	12720	454	12	.032	.0040
CGW 7740	A	959	995	S		15	8220	470	15	.038	.0043
CGW 7740	ST	959	995	S		15	12940	897	13	.031	.0039
CGW 7900	A	1508	1787	S		15	7140	565	13	.046	.007
CGW 7900	ST	1508	1787	S		15	10000	2479	9	.030	.007
CGW 7940	A	1814	1922	S		12	12490	2270	-	-	-

1/ A - Annealed, ST - Semi-tempered, T - Tempered.
2/ S indicates fracture originated on the surface of the specimen.
3/ n indicates number of specimens tested.
4/ $\overline{x}$ indicates average.
5/ S.D. indicates standard deviation.
6/ Radius of the smooth portion of the fracture face.

Amount of Temper in Specimens

Table XXVI shows the range in residual tensile stress for the various glasses in both the semi-tempered and tempered conditions. It can be seen that there is considerable difference between the maximum and minimum values for different glasses.

Since the amount of temper in the specimens showed a rather large spread in the values, Spearman's Rank Coefficient Constant was determined for the various test groups to see whether there was a correlation between the degree of temper and the strength of the specimen. The results of the analysis are presented in Table XXVII. The expected number of significant results at the five percent level in 65 tests is five percent of 65 or 3.25, whereas, the observed number of significant results is 31. This large number of significant results indicates that in a given lot of tempered glass there is a correlation between the modulus of rupture and the temper, the greater the temper the higher the strength.

Table XXVI. Range of Temper in Glass Specimens

Glass	Temper[1]	Residual Tensile Stress		Difference between maximum & minimum
		Maximum	Minimum	
		psi	psi	percent
LOF Plate	ST	4060	3430	16
	T	7585	6955	8
PPG 3235	ST	4500	3575	20
	T	7895	6570	17
PPG 6695	ST	2260	1780	21
	T	3875	2925	25
CGW 1723	ST	5660	3580	37
	T	8925	6305	29
CGW 7740	ST	2800	2060	26
CGW 7900	ST	1780	350	80

1/ ST - Semi-tempered; T - Tempered.

Table XXVII. Correlation Between Strength and Amount of Temper for Semi-Tempered and Tempered Specimens

Glass	Temper[1]	Number of Test Groups Showing Correlation at the 5% Level
LOF Plate	ST T	4 out of 10 5 out of 9
PPG 3235	ST T	3 out of 7 2 out of 7
PPG 6695	ST T	2 out of 7 2 out of 7
CGW 1723	ST T	5 out of 5 3 out of 5
CGW 7740	ST	1 out of 3
CGW 7900	ST	4 out of 5
Total		31 out of 65

1/ ST - Semi-tempered; T - Tempered.

Loss of Temper

Table XXVIII shows the loss of temper in the semi-tempered and tempered glasses after heating at the indicated temperature for 500 hours. The original amount of temper (75°F column) shows that CGW 1723 has the greatest amount of temper while CGW 7900 has such a low coefficient of expansion that it can only be tempered a small amount. The table shows that the glasses with high strain point lose only a small amount of temper when heated to 700°F for 500 hours while the glasses with a low strain point lose a considerable amount of their temper.

Table XXVIII. Change in Amount of Temper after Heating for 500 Hours at Various Temperatures

Glass	Temper[1]	Amount of Temper at 75°F	Loss of Temper after Heating								
			400°F	700°F	830°F	870°F	915°F	1130°F	1150°F	1220°F	1420°F
		psi	%	%	%	%	%	%	%	%	%
LOF Plate	ST	3835	0.9	54.2	-	96.9	-	-	-	-	-
	T	7510	-	62.0	-	97.7	-	-	-	-	-
PPG 3235	ST	3910	2.0	51.9	98.5	-	-	-	-	-	-
	T	7335	2.7	46.8	96.8	-	-	-	-	-	-
PPG 6695	ST	4274	0	6.6	-	-	64.9	100	-	100	-
	T	7595	0	12.7	-	-	72.2	100	-	100	-
CGW 1723	ST	4555	0	4.5	-	-	-	-	99.0	-	-
	T	8050	1.03	6.7	-	-	-	-	99.5		
CGW 7740	ST	2400	0	57.2	-	100	-	-	-	-	-
CGW 7900	ST	1370	0.5	0.8	-	-	-	-	-	-	95.9

1/ ST - Semi-tempered; T - Tempered.

Young's Modulus Determined at Elevated Temperatures

Young's modulus was determined by the dynamic method at temperatures up to the strain point on three annealed specimens of each of the glasses in the test program. Specimens from the same lot as those tested for the modulus of rupture were used. The results are presented in Figure 9 and show that the Young's modulus of LOF Plate, PPG 3235, PPG 6695 and CGW 1723 decreases as the temperature increases. The Young's modulus of CGW 7740, CGW 7900, and CGW 7940, all initially increased as the temperature increased. It is interesting to note that the four glasses that had decreasing Young's moduli with increasing temperature are the same glasses that had initially decreasing moduli of rupture with increasing temperature. The three glasses that showed an increase in Young's moduli with temperature are the glasses that also showed an increase in moduli of rupture with temperature.

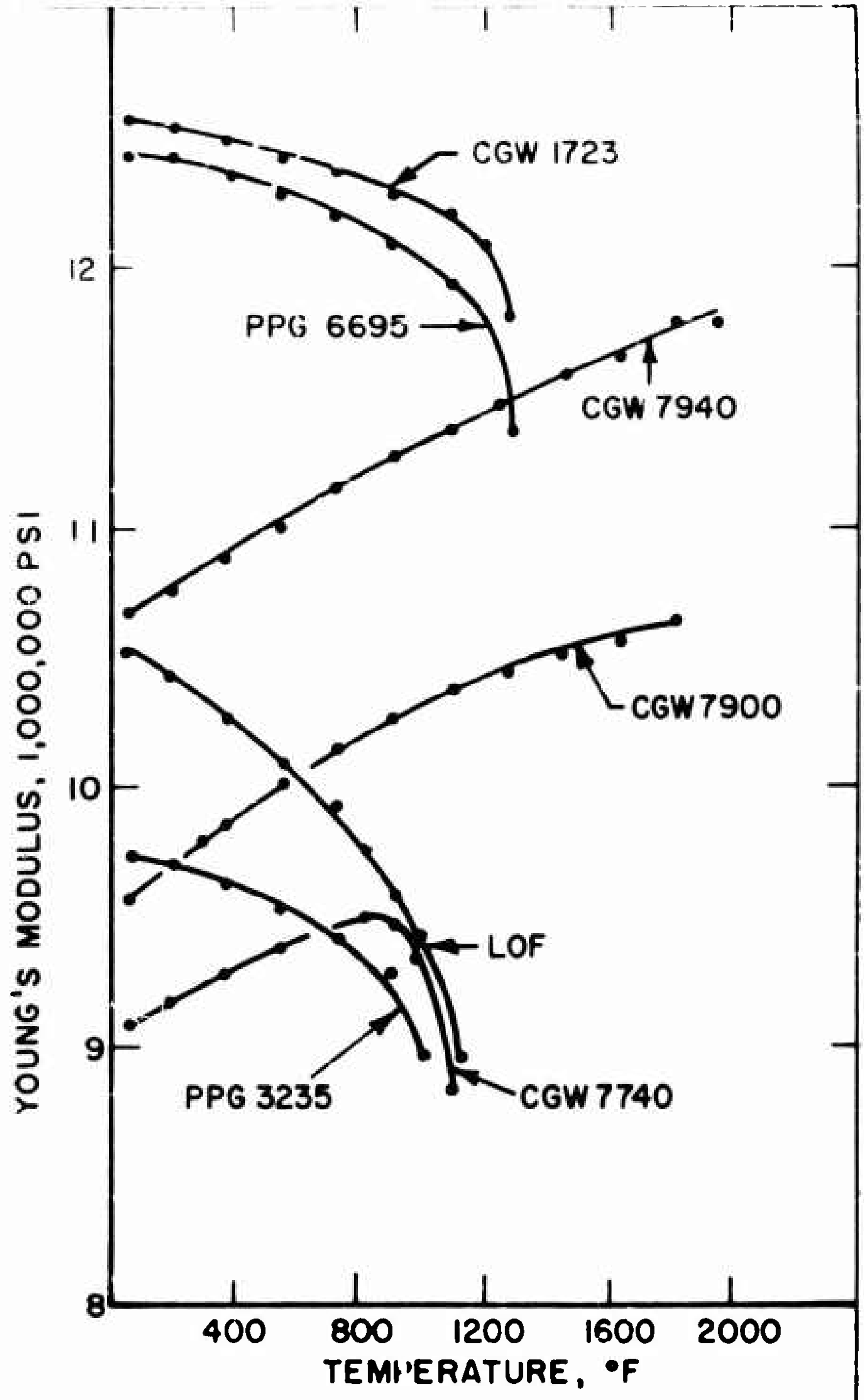


FIGURE 9 YOUNG'S MODULUS AT ELEVATED TEMPERATURES

Young's Modulus Determined at 75°F Before and After Heating for 500 Hours at Various Temperatures

Young's modulus results determined at 75°F before and after heating for 500 hours are presented in Table XXIX. The actual value of Young's modulus determined at 75°F before heating and the percent change in this value caused by heating to the indicated temperature are presented. It can be seen that with the exception of CGW 7900 and CGW 7940 the Young's modulus tended to increase with temperature. CGW 7940 showed no change after heating while the decrease in CGW 7900 semi-tempered specimens is probably due to the devitrification of the surface of these specimens.

The glasses capable of being tempered to some degree had a Young's modulus that was greatest for the annealed glass, slightly lower for the semi-tempered glass, and still lower for the tempered glass. These differences are statistically significant at the 5% level with the exception of the differences between the semi-tempered and tempered specimens for PPG 3235 and PPG 6695. After heating at the higher temperature Young's modulus for all three conditions of temper tended to approach each other at a new value higher than the original annealed value.

It should be noted that the Young's modulus values given in Table XXIX were determined at 75°F before and after heating for 500 hours at the indicated temperatures. Young's modulus values determined on the same types of glass after different heat treatments would give somewhat different values than those presented here (10).

Table XXIX. Change in Young's Modulus at 75°F After 500 Hours Exposure to Various Temperatures

Glass	Temper[1]	75°F 10^6 psi[2]	400°F Percent[3]	700°F Percent	830°F Percent	870°F Percent	915°F Percent	1130°F Percent	1150°F Percent	1220°F Percent	1420°F Percent	1724°F Percent
LOF Plate	A	10.50	-	+1.14		+2.87						
	S	10.34	+.48	+2.81		+4.34						
	T	10.16	-	+2.95		+5.20						
PPG 3235	A	9.97	+.20	+1.68	+4.47							
	S	9.80	-.20	+3.44	+6.87							
	T	9.77	0	+4.29	+7.83							
PPG 6695	A	12.47	0	+ .40			+1.20	+2.80		+2.24		
	S	12.16	+.08	+1.15			+3.21	+4.75		+3.97		
	T	12.12	+.16	+1.15			+4.53	+5.61		+4.53		
CGW 1723	A	12.62	0	+ .16					0			
	S	11.93	0	+ .25					+5.61			
	T	11.85	0	+ .51					+5.81			
CGW 7740	A	9.11	0	+1.29		+2.30						
	S	9.00	+.22	+2.76		+4.72						
CGW 7900	A	9.49	0	- .52							- .10	
	S	9.56	+.10	0							-2.82[4]	
CGW 7940	A	10.50	0	0								0

1/ A indicates annealed; S indicates semi-tempered; T indicates tempered.
2/ Average Young's modulus determined at 75°F.
3/ Change in Young's modulus over 75°F Young's modulus.
4/ Surfaces devitrified.

Poisson's Ratio

Values for Poisson's ratio are given in Table XXX. These results were obtained at the same time the dynamic Young's modulus results presented in Table XXIX were obtained. Poisson's ratio was not determined directly but was calculated from the Young's modulus and the shear modulus. The modulus of elasticity in shear at both room and elevated temperatures changed in the same proportion as Young's modulus with the net result being that the Poisson's ratio values were not measurably affected by temper or heat treatment.

Table XXX. Poisson's Ratio Determined at 75°F

Glass	Poisson's Ratio		
	Annealed	Semi-Tempered	Tempered
LOF Plate	0.202	0.205	0.196
PPG 3235	.212	.217	.216
PPG 6695	.246	.244	.251
CGW 7740	.189	.194	-
CGW 1723	.236	.240	.242
CGW 7900	.168	.175	-
CGW 7940	.151	-	-

PART III

ADDITIONAL DATA

The results presented here were obtained either before, or simultaneously with, the main program data. This data is presented here in order to keep the main program presentation simple and straightforward, and consists of:

1) Effect of cut edges on the modulus of rupture.

2) Comparison of the effect of temperature on the modulus of rupture of sandblasted and ground and polished specimens.

3) Effect of different types of sandblasting on the modulus of rupture.

4) Effect of the rate of loading on the modulus of rupture.

5) Modulus of rupture results on specimens previously tested for static fatigue.

6) Distribution of strength results.

7) Relation of the mirror size to the modulus of rupture.

Effect of Cut Edges on the Modulus of Rupture

Ground and polished specimens were cut by three different laboratories from the same lot of glass used for the Part I testing. One laboratory (A) cut specimens from this lot on two different occasions and in addition, cut specimens from the same type of glass used in the Part I testing but from a different lot. The specimens were tested on the same apparatus and in the same manner but not at the same time. The results are presented in Table XXXI and show that there is no statistical difference (1% level) between the two groups of specimens from the same lot that were cut by Laboratory A (Groups A-1 and A-2). The results from Laboratory B and Laboratory C show no statistical difference between them, but the strength of both is significantly lower than the strength results from Laboratory A. The modulus of rupture of the other lot (A-3) of glass cut by Laboratory A is significantly lower than the other moduli obtained from specimens cut by this laboratory.

Table XXXI. Effect of Cutting on the Modulus of Rupture of Annealed LOF Plate Glass Ground and Polished Specimens

	A-1	A-2	A-3	B	C
Average Modulus of Rupture (psi)	14,400	13,600	11,300	11,900	10,500
Standard Deviation (psi)	4,400	3,610	2,550	3,040	3,220
Number of Specimens	23	30	30	30	30
Surface Breaks	10	10	12	11	6
Edge Breaks	13	20	18	19	24
Average Modulus of Rupture (psi) Surface Breaks	14,300	14,600	11,300	10,700	10,600
Average Modulus of Rupture (psi) Edge Breaks	14,600	13,100	11,300	12,500	10,500

A-1. Samples of LOF Plate glass cut by Laboratory A.

A-2. Sample of glass from lot A-1 cut by Laboratory A at a different time.

A-3. Samples of same type of glass but from different lot. Cut by Laboratory A.

B. Samples of glass from same lot as A-1. Cut by Laboratory B.

C. Samples of glass from same lot as A-1. Cut by Laboratory C.

It is interesting to note that in all five groups the number of edge breaks exceeds the number of surface breaks, with edge breaks comprising from 56% to 80% of the total. Comparing the average modulus of rupture for surface and edge breaks shows that one is not consistently different from the other and in three of the five cases are quite close together.

The results show that there may be an effect on the strength of glass caused by the cutting of the specimens by different individuals.

Comparison of the Effect of Temperature on the Modulus of Rupture of Sandblasted and Ground and Polished Specimens

Thirty ground and polished and ten sandblasted specimens were tested at 75°F, 400°F, and 550°F, all after less than one hour exposure to the test temperature. The results are presented in Table XXXII. The average modulus of rupture of the ground and polished specimens was slightly higher at 75°F than at 400°F and 550°F but that the difference was not a statistically significant amount (1% level). It should be noted that the large standard deviation of the ground and polished specimens serves to mask any but large differences between groups. The modulus of rupture of the sandblasted specimens was lowered a statistically significant amount at both 400°F and 550°F as compared to 75°F. There was no significant difference between the 400°F and 550°F results for the sandblasted specimens.

Table XXXII. Effect of Temperature on the Modulus of Rupture of Annealed LOF Plate Glass Specimens

Condition of Surface	75°F				400°F				550°F			
	Location of Fracture 1/	Modulus of Rupture			Location of Fracture	Modulus of Rupture			Location of Fracture	Modulus of Rupture		
		n 2/	$\overline{x}$ 3/	S.D. 4/		n	$\overline{x}$	S.D.		n	$\overline{x}$	S.D.
Sandblasted	S	10	8210	1110	S	10	6460	990	S	9	6840	765
	E	0			E	0			E	1	7290	-
Ground and Polished	S	10	14560	4230	S	7	14380	3720	S	12	13910	3550
	E	20	13070	-	E	23	12170		E	18	11860	

1/ S - indicates fracture originated on the surface of the specimen.
E - " " " " " edge " " " .

2/ n - indicates number of specimens.

3/ $\overline{x}$ - indicates average.

4/ S.D. - indicates standard deviation.

Effect of Different Sandblasting on the Modulus of Rupture

Table XXXIII gives the modulus of rupture results at 75°F for LOF Plate glass sandblasted by different methods. The results show that different amounts of abrasion can affect the strength of glass. The methods of sandblasting were varied by using different grain sizes of sand and different amounts of air pressure to blow the sand against the specimen.

Table XXXIII. Effect of Different Sandblasting on the Modulus of Rupture of Annealed LOF Plate Glass Specimens

Group	Fracture Origin	Number of Specimens	Average Modulus of Rupture	Standard Deviation
1	S	19	10240	446
	E	5	9410	735
2	S	10	8210	1109
	E	0	0	0
3	S	9	6900	579
	E	6	5030	779

The Effect of the Rate of Loading on the Modulus of Rupture

The modulus of rupture was determined on groups of 15 annealed, sandblasted specimens of PPG 3235 glass tested at several rates of loading. The specimens were from the same lot, and were the same size as those used in the main program (Part II) testing. The testing was conducted at 75°F on the same apparatus and with the same technique as used for the other modulus of rupture work except for varying the loading rates. A graph of the results obtained is shown in Figure 10. In addition, the data presented by Black (10) and Orr (11), are presented for comparison. The data of Black and Orr were obtained on ground and polished specimens of a different size and a different glass composition than used for the NBS work. However, the interesting point is that although all three curves show an increase in strength with increase in loading rate, the rate of increase for the ground and polished specimens is much greater than for the sandblasted specimens.

Modulus of Rupture of LOF Plate Glass Determined on Survivors of the Stress-Rupture and Creep Testing

The modulus of rupture was determined, at 75°F, on the LOF specimens that survived the 500 hour stress-rupture test as well as those specimens tested at 870°F that exhibited creep. The average value of the modulus of rupture for each group of survivors is presented in Table XXXIV. The stress-rupture specimens tested at 75°F and 400°F survived 500 hours at the indicated stress and temperature. The specimens tested at 870°F were held at this temperature and under the indicated stress for a maximum of 50 hours; for at this time the amount of creep had become excessive for the apparatus, and the testing stopped.

These tests were made to compare the modulus of rupture of specimens tested under different conditions of stress and temperature, and also compare these values to the modulus of rupture of specimens that were not previously stressed.

The results in Table XXXIV show that for the annealed specimens there is no statistical difference between the modulus of rupture of the two groups, stressed at 870°F and 400°F, during the stress-rupture test.

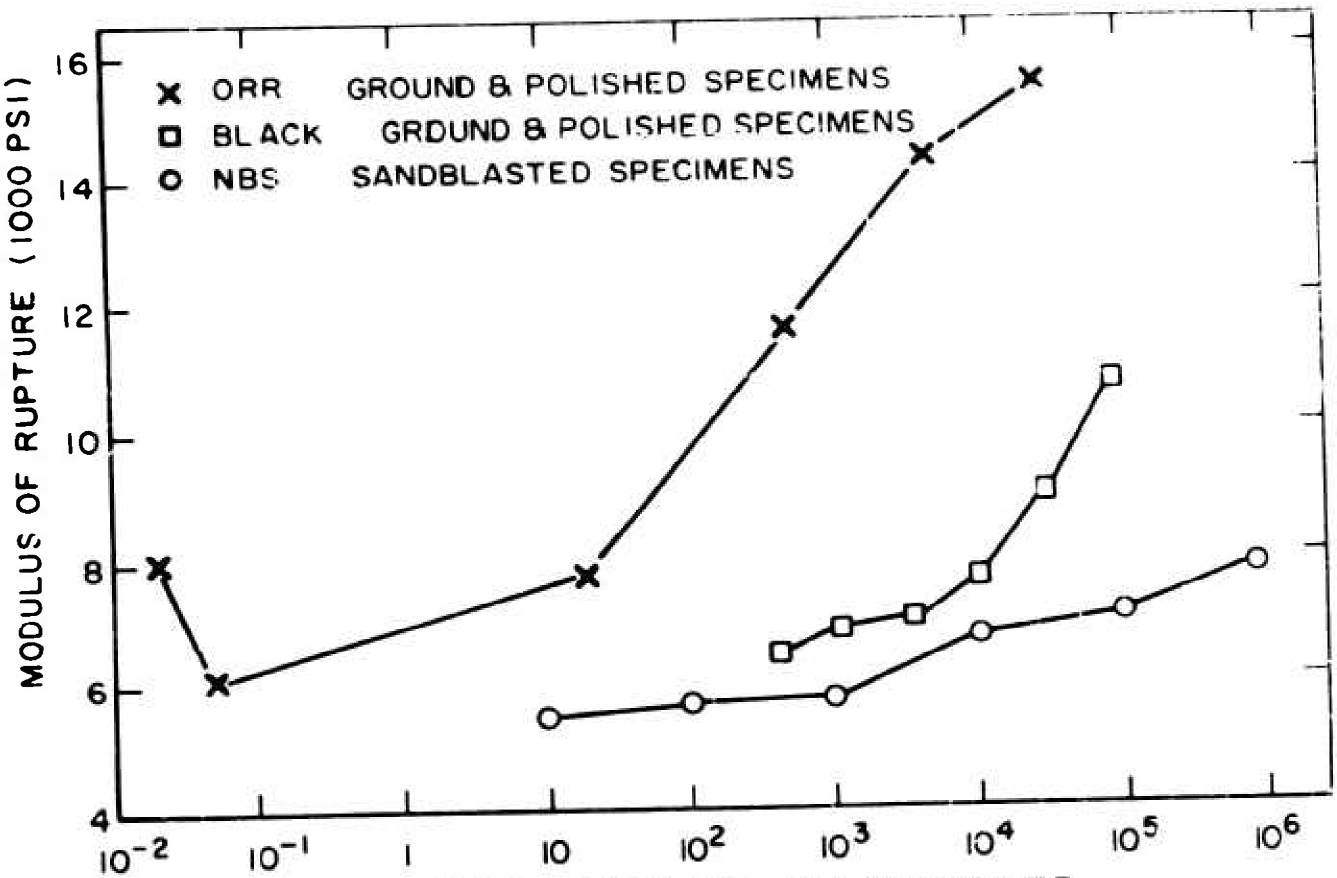


FIGURE 10 THE EFFECT OF THE RATE OF LOADING ON THE MODULUS OF RUPTURE OF ANNEALED, SANDBLASTED, PPG 3235 SPECIMENS

Table XXXIV. Modulus of Rupture Determined at 75°F on Sandblasted LOF Plate Glass Specimens that Survived the Static Fatigue and Creep Testing

Amount of Temper[1]	Temperature at which Stressed °F	Stress[2] %	Location of Break[3]	Modulus of Rupture n[4]	$\bar{x}$[5] psi	S.D.[6] psi	Mirror Size[7] n	$\bar{x}$ Inches	Birefringence Before Heating n	$\bar{x}$ mu/in	Birefringence After Heating n	$\bar{x}$ mu/in
A	870	60	S	5	6760	1135	5	.C55				
	870	60	E	5	6560		5	.068				
A	400	60	S	8	7100	652	8	.052				
	400	60	E	0								
ST	870	60	S	1	10000		1	.030	1	1685	1	225
	870	60	E	7	8030		7	.069	7	1841	7	186
ST	870	75	S	4	9000	1838	4	.047	4	1826	4	237
	870	75	E	3	6430		3	.056	3	1846	3	116
ST	870	90	S	2	6200	990	2	-	2	1695	2	125
	870	90	E	6	8500		6	.048	6	1842	6	210
ST	400	60	S	10	15070	397	10	.032	10	1793	10	1691
	400	60	E	0								
ST	400	75	S	10	15090	387	10	.032	10	1784	10	1689
	400	75	E	0								
ST	400	90	S	6	15630	507	6	.030	6	1830	6	1751
	400	90	E	0								
ST	75	60	S	10	14340	670	10	.036	10	1808		
	75	60	E	0								
ST	75	75	S	8	14830	1161	8	.035	8	1843		
	75	75	E	0								
T	870	60	S	5	7900	1651	5	.078	5	3462	5	488
	870	60	E	5	7360		5	.057	5	3663	5	680
T	870	75	S	3	13570	2871	3	.029	3	3426	3	828
	870	75	E	4	8800		3	.044	4	3509	4	583
T	870	90	S	6	12020	2550	5	.031	6	3531	6	1032
	870	90	E	4	10725		4	.029	4	3492	4	708
T	400	60	S	10	22660	577	10	.030	10	3519	10	3380
	400	60	E	0								
T	400	75	S	10	22720	388	10	.030	10	3536	10	3398
	400	75	E	0								
T	400	90	S	8	22270	828	8	.031	10	3456	10	3384
	400	90	E	0								
T	75	60	S	10	22130	690	10	.033	10	3547	10	3506
	75	60	E	0								
T	75	75	S	10	22380	543	10	.031	10	3492	10	3441
	75	75	E	0								
T	75	90	S	2	24100		2	.026	2	3815	2	3797
	75	90	E	0								

1/ A - annealed, ST - semi-tempered, T - tempered.

2/ Stress applied to specimens. Presented as a percent of the average modulus of rupture determined at the indicated temperature.

3/ S indicates fracture originated on the surface of the specimen.
E " " " " " edge " " " .

4/ n indicates number of specimens tested.

5/ $\bar{x}$ indicates average.

6/ S.D. indicates standard deviation.

7/ Radius of the smooth portion of the fracture face.

For the semi-tempered specimens there is no statistical difference between the modulus of rupture of any of the groups stressed at 75°F and 400°F. The specimens stressed at 870°F had lower strengths than the specimens stressed at 75°F and 400°F. however, this is not surprising since the amount of strain remaining in these specimens was small. There was no statistical difference between the groups stressed at 870°F when comparing averages that included surface and edge breaks. Comparing the surface break average only would be meaningless because of the large number of edge breaks.

The results of the tempered specimens show there are no statistical differences between the specimens stressed at 75°F and 400°F. The specimens stressed at 870°F had significantly lower modulus of rupture than those stressed at 75°F and 400°F. There were differences in the strength of the groups of specimens stressed at 870°F, the strength of the groups depending largely on the amount of temper remaining.

The moduli of rupture for annealed, semi-tempered, and tempered LOF Plate Glass specimens tested at 75°F and not previously stressed are, respectively: 6900 psi, 13410 psi, and 21990 psi. Comparing these values to the values obtained after stressing for 500 hours at 75°F and 400°F and presented in Table XXXIV shows that stressing for 500 hours at the two indicated temperatures did not significantly weaken the glass in any of the three conditions of temper.

Distribution of Strength Results

Knowledge of the type of distribution of results of strength tests is important so that useful statistical analyses can be made. There is a difference of opinion as to the type of distribution that best describes a glass sample tested for strength, so in an attempt to clarify the picture the following work was done. Six hundred PPG Plate Glass specimens were tested. The specimens were the same size as used for the remainder of the test program and came from a single lot of commercially produced plate glass. Three hundred specimens were tested with the original ground and polished surfaces and three hundred had the surfaces sandblasted in the same manner as for the regular program. Specimens were measured for the degree of anneal, refractive index and thickness before testing and all these measurements indicated there were no unusual discontinuities among the specimens. The three hundred

specimens of each surface type were divided into two groups so in effect there were four groups of 150 specimens each that were tested at 75°F.

Four types of distribution for the results were tried: log-normal, extreme value, Weibull, and normal. Two log-normal and extreme value were not satisfactory in describing the data. The Weibull distribution gave results that were inconclusive. Three of the four test groups fit the normal distribution. Figures 11 through 13 show the test groups plotted on normal probability paper. A chi-square test also confirmed the normality of three of the test groups and the non-normality of the fourth.

This analysis indicates the modulus of rupture values of a glass sample generally assumes a normal distribution and analysis of the strength of glass can be made on the basis of this assumption.

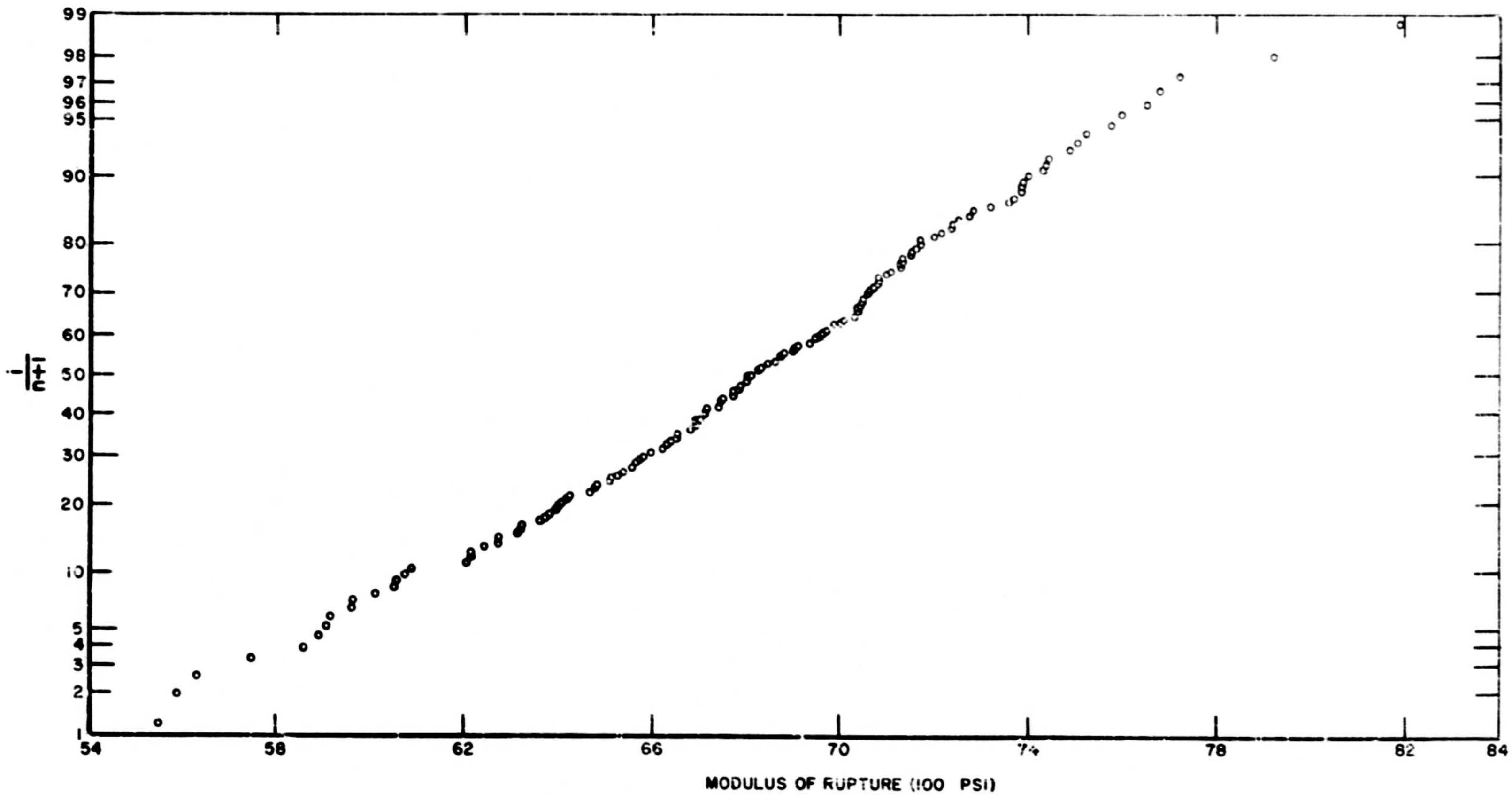


FIGURE 11 DISTRIBUTION OF MODULUS OF RUPTURE OF SANDBLASTED GROUP A ASSUMING NORMAL PROBABILITY DISTRIBUTION

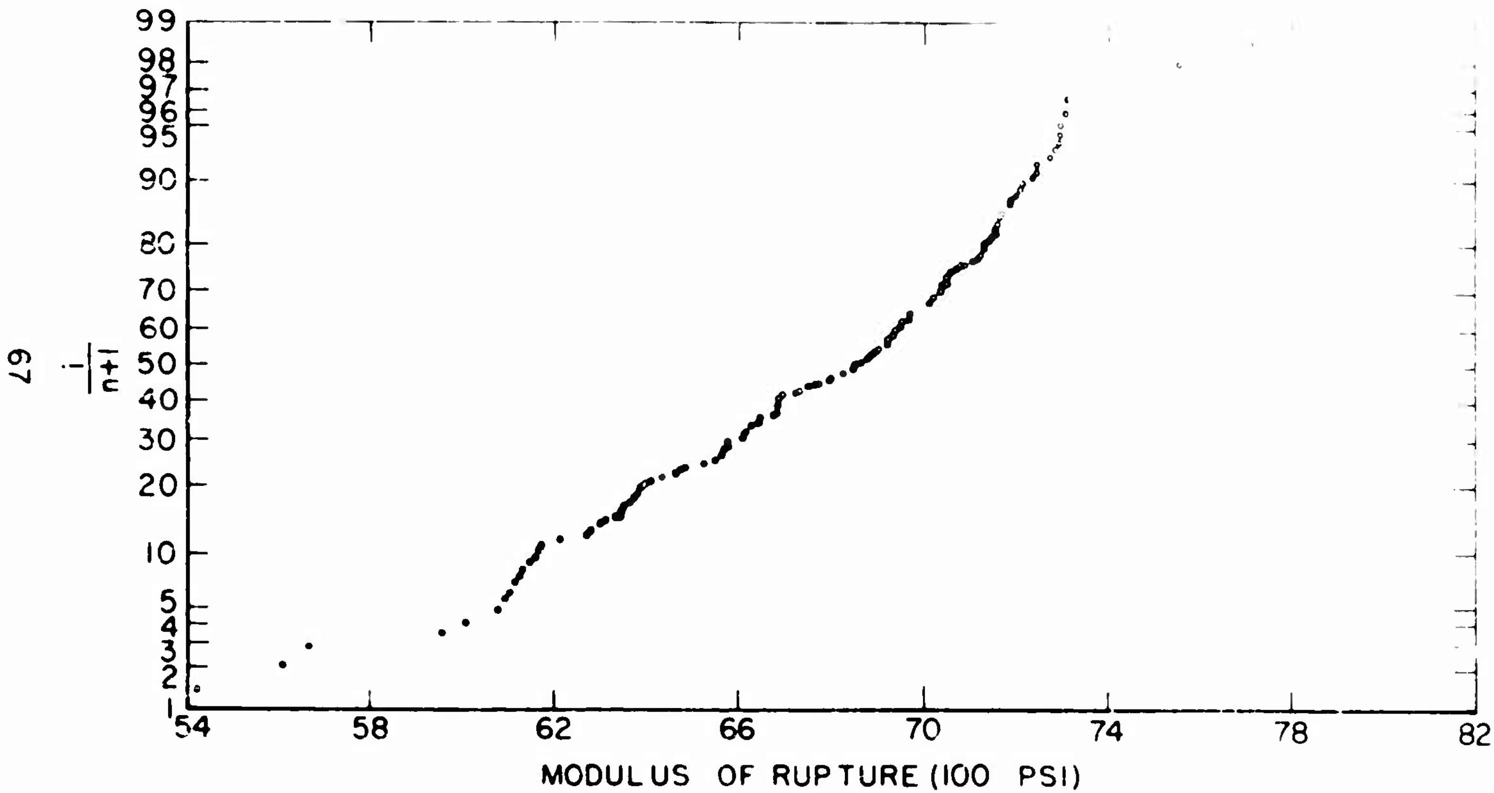


FIGURE 12 DISTRIBUTION OF MODULUS OF RUPTURE OF SANDBLASTED GROUP B ASSUMING NORMAL PROBABILITY DISTRIBUTION

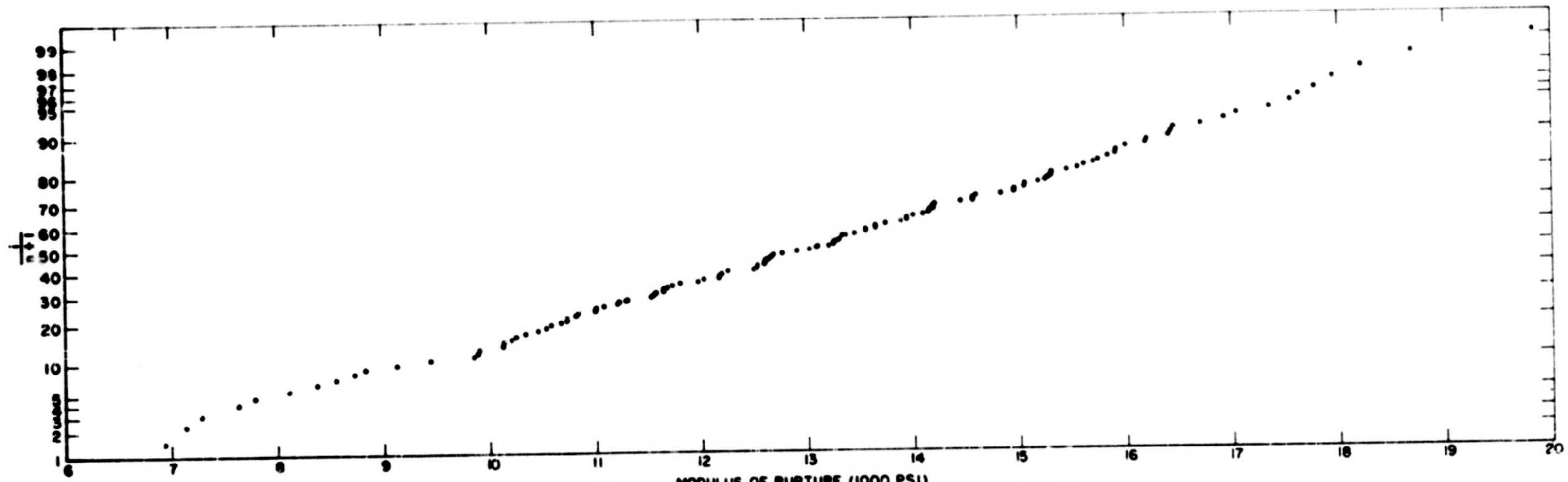


FIGURE 13 DISTRIBUTION OF MODULUS OF RUPTURE OF GROUND & POLISHED GROUP C ASSUMING NORMAL PROBABILITY DISTRIBUTION

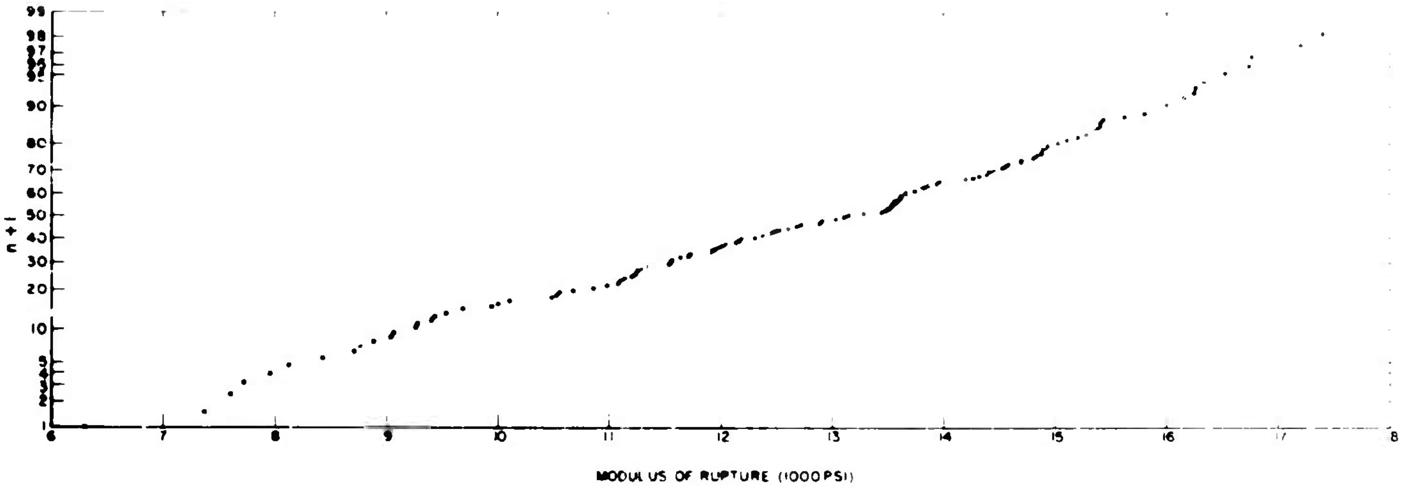


FIGURE 14 DISTRIBUTION OF MODULUS OF RUPTURE OF GROUND & POLISHED GROUP D ASSUMING NORMAL PROBABILITY DISTRIBUTION

Mirror Size

When glass fractures, the area immediately surrounding the fracture origin is smooth and is referred to as the mirror portion of the fracture face. There is an inverse relationship between the size of this mirror and the strength of the glass. The results obtained on the glasses in the program are shown in Figures 15 through 18. These results were obtained from the modulus of rupture specimens.

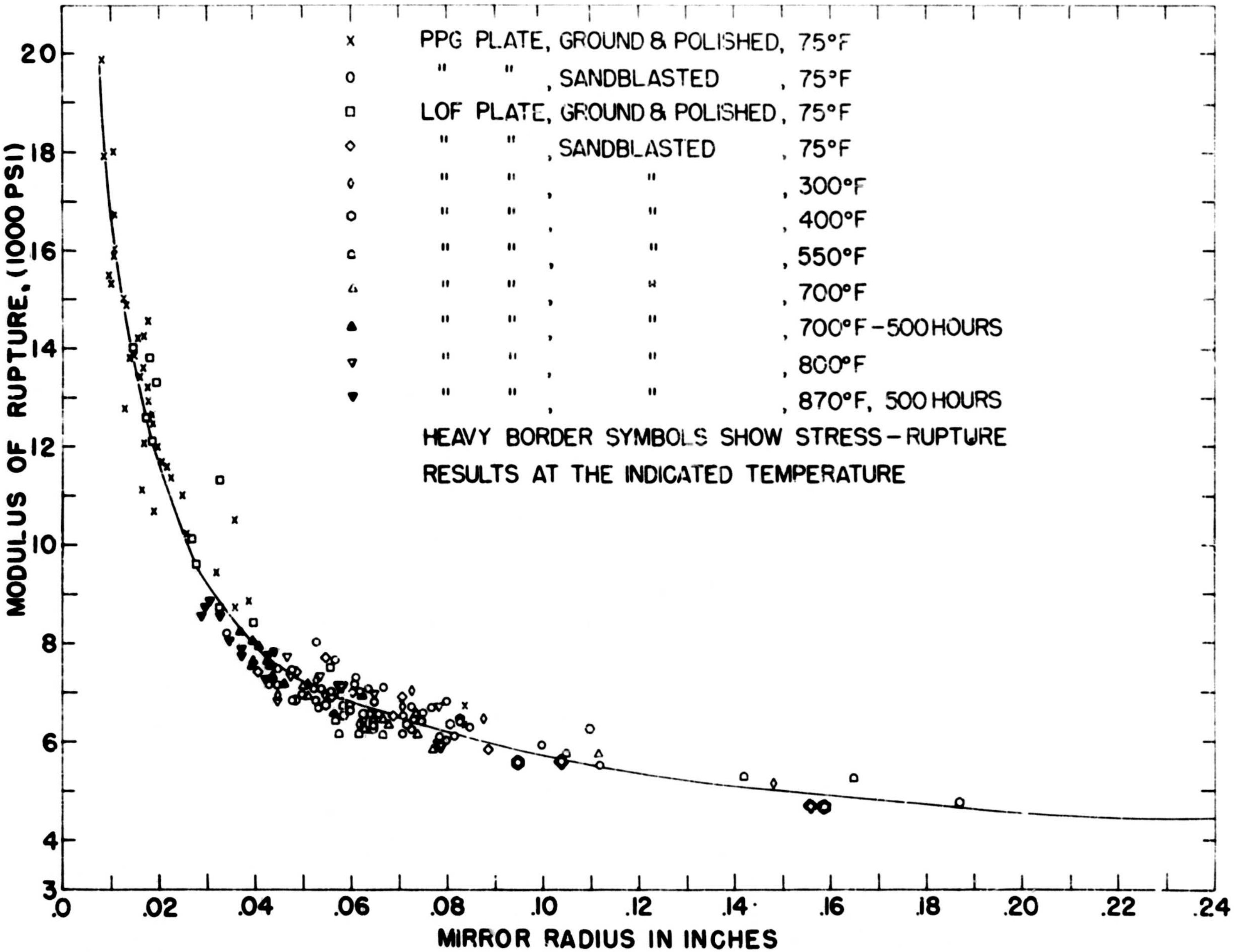


FIGURE 15 MODULUS OF RUPTURE VERSUS MIRROR SIZE FOR PLATE GLASS

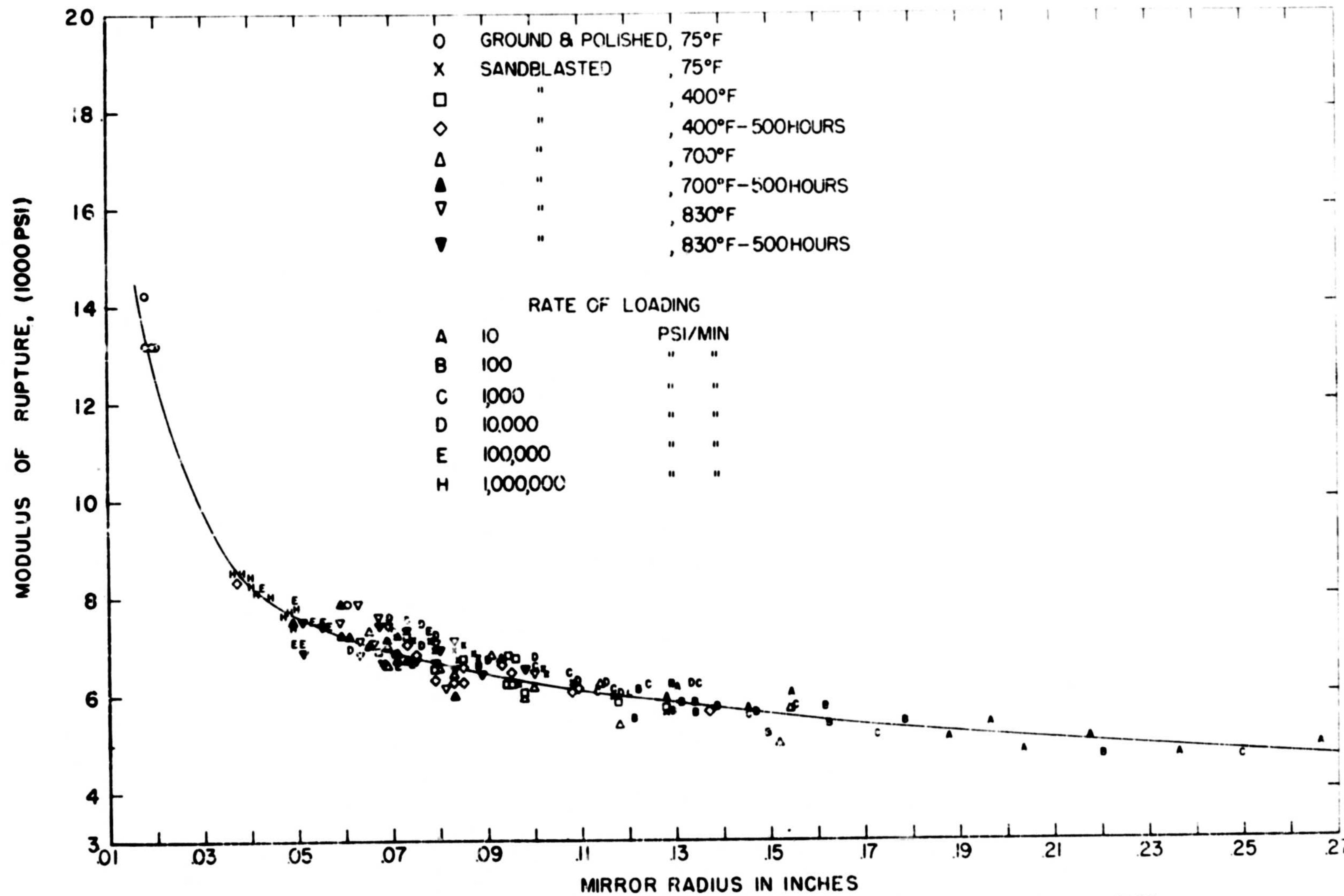


FIGURE 16 MODULUS OF RUPTURE VERSUS MIRROR SIZE FOR PPG 3235

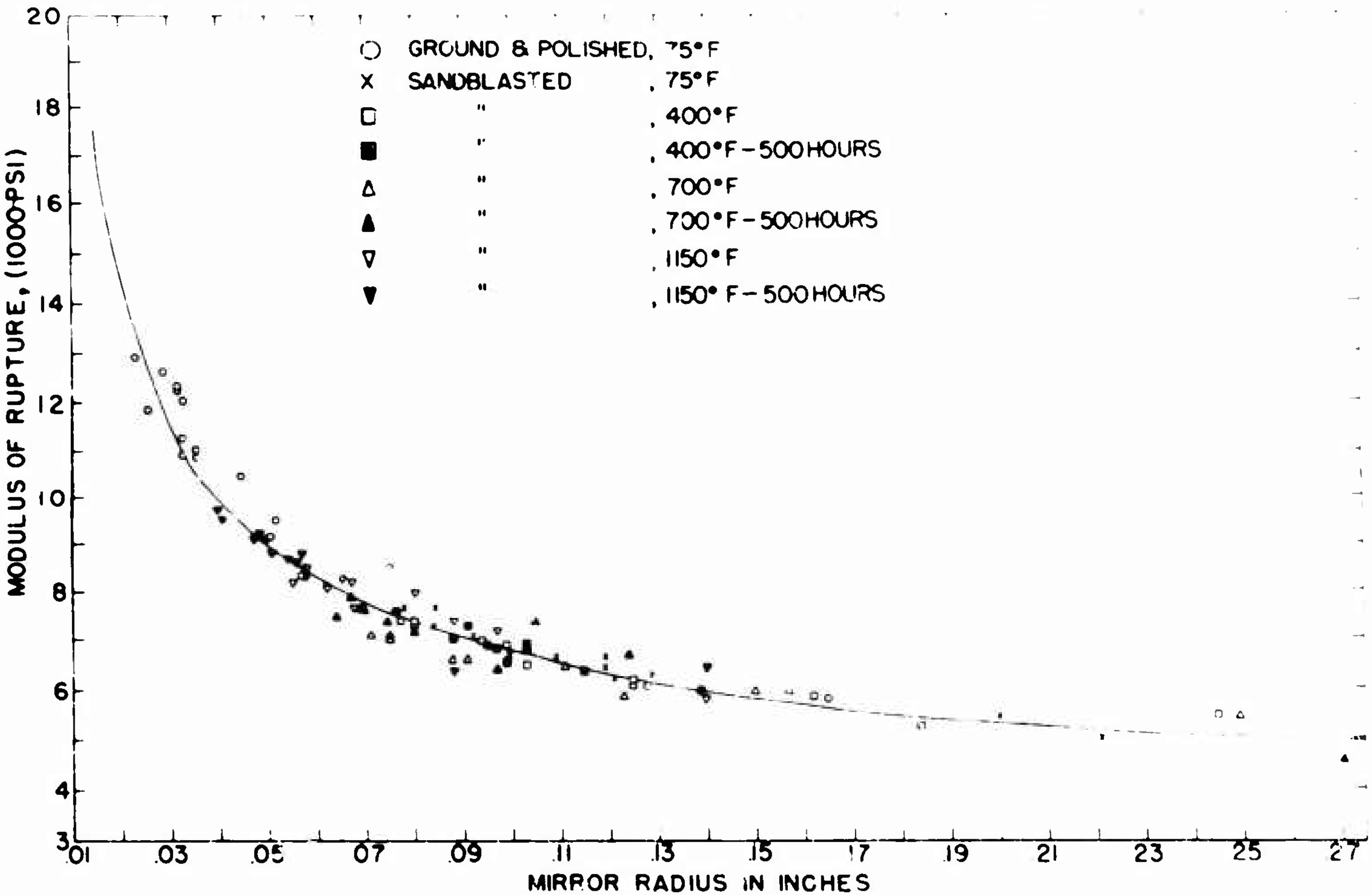


FIGURE 17 MODULUS OF RUPTURE VERSUS MIRROR SIZE FOR CGW 1723

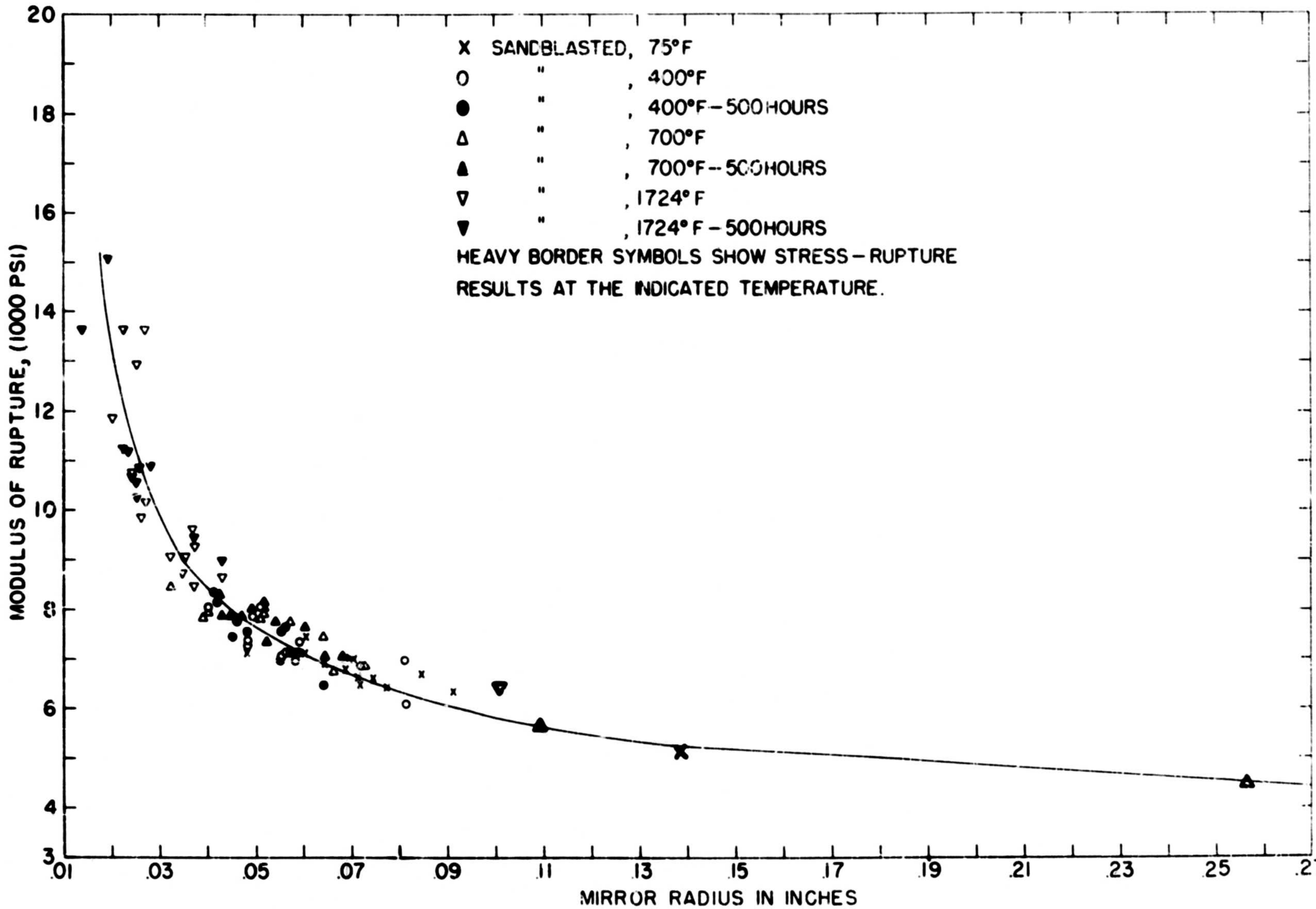


FIGURE 18 MODULUS OF RUPTURE VERSUS MIRROR SIZE FOR CGW 7940

Inspection of Figures 15, 16, 17, and 18 shows that the data for a particular glass fell along the curve describing that glass irrespective of surface conditions of the glass, rate of loading, time under load, and temperature of test. Figure 16 shows the data for PPG 3235. The symbols show the data obtained by testing at various temperatures. The letters show the data obtained during the rate of loading experiment, conducted at 75°F. Comparing the mirror sizes at a constant stress showed that the factors noted above did not affect the mirror size. All determinations were made on the same size specimens so no effect of size was studied. Examination of the curves and the comparisons of mirror size at constant stress for a particular glass showed that other than the effect of strength on mirror size there was essentially no difference between the mirror sizes of: 1) Specimens having ground and polished surfaces and specimens having sandblasted surfaces, 2) Specimens broken at different rates of loading in the modulus of rupture testing, 3) Specimens tested at different test temperatures. This was true whether tests were made with less than one hour exposure or after 500 hours exposure at the testing temperature.

Figure 19 is a graph of the four curves plotted together to show the relationship between them. It can be seen that the curves are parallel but displaced from one another, indicating that the type of glass has an effect on the location of the curve. The results show that of all of the factors investigated the only one affecting the relationship between mirror size and modulus of rupture is the type of material.

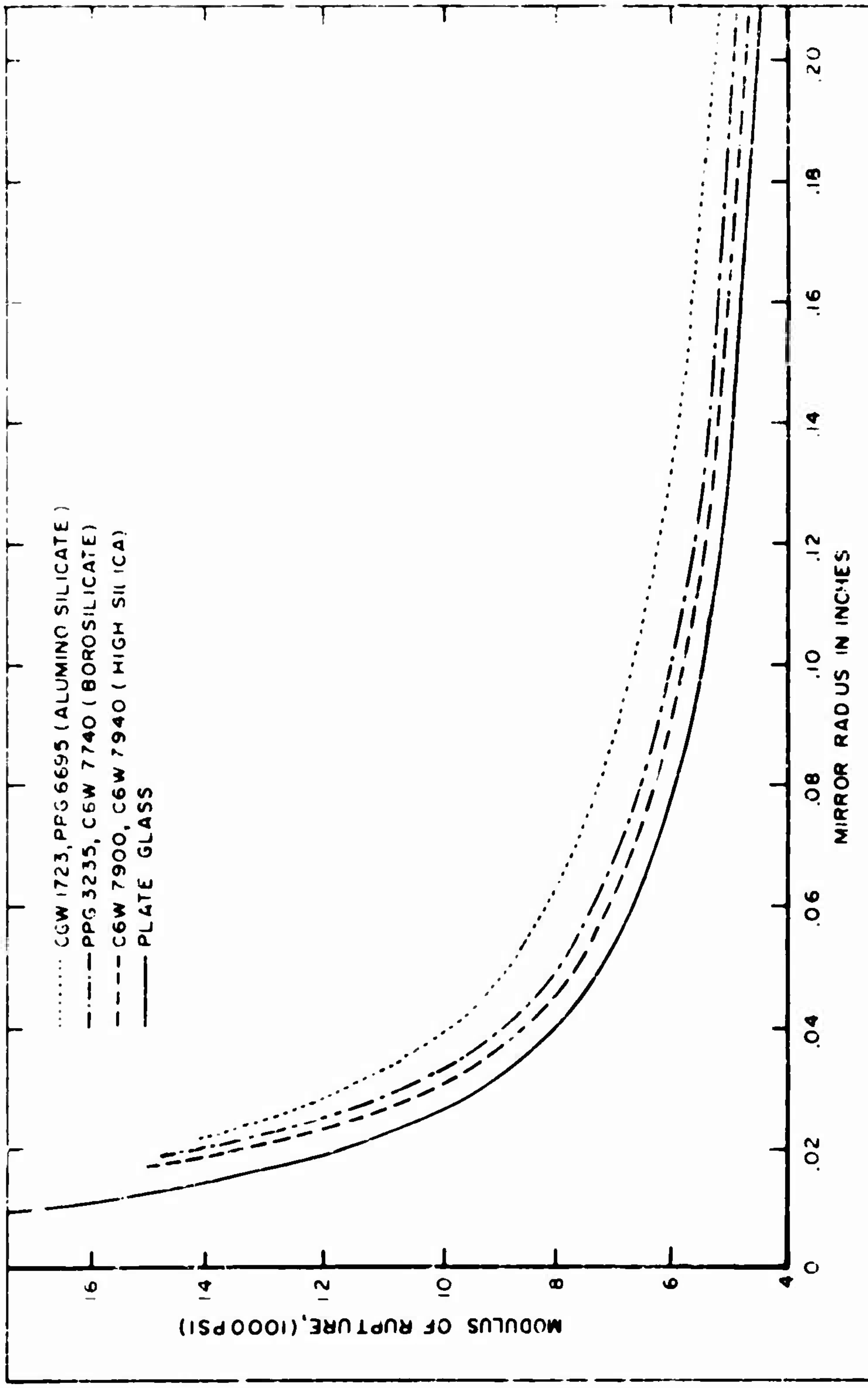


FIGURE 19 MODULUS OF RUPTURE-MIRROR RADIUS CURVES FOR FOUR TYPES OF GLASS

CONCLUSIONS

The following conclusions were developed from the data obtained in the test program. Some, as mentioned in the introduction, have been previously reported by other authors; but they are presented here because they were derived from the present work and also give further confirmation to the previous findings.

1) Satisfactory results were obtained by the method reported for measuring modulus of rupture. This method followed ASTM procedures except for the use of two point loading. Other alterations or modifications may interfere with the modulus of rupture test. The results showed that a rod in contact with the tensile surface of a test specimen will significantly reduce the strength of the glass.

2) In addition to reporting the average modulus of rupture, the standard deviation or coefficient of variation and the number of specimens tested should be reported.

3) The location of the fracture origin should be reported as the distance from the loading knife edge or in the case of two point loading, fracture origins that occur outside the area of uniform stress between the loading knife edges should be reported as well as the distance from a loading knife edge. This information can be used to determine the actual stress at which the glass failed and not the stress which a portion of the glass withstood.

4) An analysis of the data shows that glass with fractures originating on the surface may be significantly stronger than glass with fractures originating on the edge. This should be considered in reporting strength results.

5) Modulus of rupture tests conducted under similar conditions and on the same kind of glass at different laboratories, or possibly at the same laboratory, can give statistically different results and yet show no laboratory bias.

6) Abrading the surface of the specimens reduces the scatter in the results and lowers the strength. Carefully controlled, uniform surface abrasion may be useful in reducing the number of specimens required to make comparative tests between groups of the same glass under different conditions. Since the strength of glass is largely

dependent upon the surface of the glass the results obtained with abraded specimens should in no way be construed to be used as the absolute value of the strength of the glass in question.

7) The cut edges may affect the strength of glass.

8) The rate of loading will affect the strength of glass, the faster the rate of loading the higher the strength. However, this effect appears to be less noticeable in specimens with abraded surfaces than in specimens with ground and polished surfaces.

9) The modulus of rupture determined on specimens that had undergone static fatigue testing was not changed from specimens that were tested without being subject to static fatigue.

10) The four annealed glasses having the lowest silica content and highest coefficient of expansion, showed as the temperature increased, a decrease in strength followed by an increase in strength as the strain point was approached. The decreases in strength varied from 6% to 15% below the 75°F modulus of rupture value. This decrease and increase in strength with increasing temperature was observed in sandblasted LOF Plate Glass at NBS in the preliminary program, in the main program, and in comparing the effect of temperature on sandblasted and ground and polished specimens. The same phenomenon was observed by Corning Glass Works (13) when it performed similar tests on CGW 1723.

Young's modulus showed a continuous decrease with increasing temperature for the above four glasses.

11) The three glasses with the higher silica content and the lower coefficients of expansion showed a continuous increase in strength with increase in temperature. Other workers have observed this in the case of fused silica (14). Young's modulus increased with increasing temperature for these three glasses up to the beginning of the transformation region.

12) For annealed glass, heating for 500 hours at a particular temperature increased its strength when compared to the same glass untreated.

13) Testing semi-tempered specimens with less than one hour exposure to a testing temperature showed that these glasses tended to retain their strength to near the strain point. Tempered glass tested under the same conditions lost appreciable amounts of strength at temperatures below the strain point.

14) After heating for 500 hours both semi-tempered and tempered glasses lost appreciable amounts of strength at temperatures well below the strain point.

15) After heating for 500 hours at 120°F below the respective strain points of the glasses the semi-tempered and tempered specimens, when measured optically, showed they were annealed. However, in every case these specimens were stronger than the annealed specimens heated for 500 hours at the same temperature.

16) Statistical analysis of the data showed that there is a correlation between the amount of temper and the strength in the semi-tempered and tempered specimens; the greater the temper the higher the strength.

17) A statistical study of the distribution of strength showed that out of four theoretical distributions the normal distribution was the best for describing the data for glass and appeared to be adequate for obtaining the parameters necessary for a statistical analysis of the strength of glass.

18) For annealed glass the relationship between the mirror portion of the fracture face and the strength of glass is not affected by the condition of the surface, temperature, or rate of loading; but is different for different types of glasses.

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Rpt Nr WADC-TR-56-645, Pt VII. PROPERTIES OF GLASSES AT ELEVATED TEMPERATURES. Interim report, Aug 62, 80pp, incl illus, tables, & 14 refs.

Unclassified Report

A program was initiated to investigate the physical properties of several glasses that are candidates for glazing flight vehicles. The objectives of the program were: 1) Develop suitable test methods for determining the desired physical properties at room and elevated temperatures, and 2) determining the values of the desired physical properties

(over)

of individual glasses over a wide temperature range.

This report contains a study and interpretation of several factors associated with the determination of Young's modulus and the modulus of rupture. The tests were performed on seven commercially available glasses and were conducted from room temperature to several degrees above their strain points.

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III. Nat'l Bureau of Standards, Washington, D. C.
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